Searching for DM with Sounding Rockets

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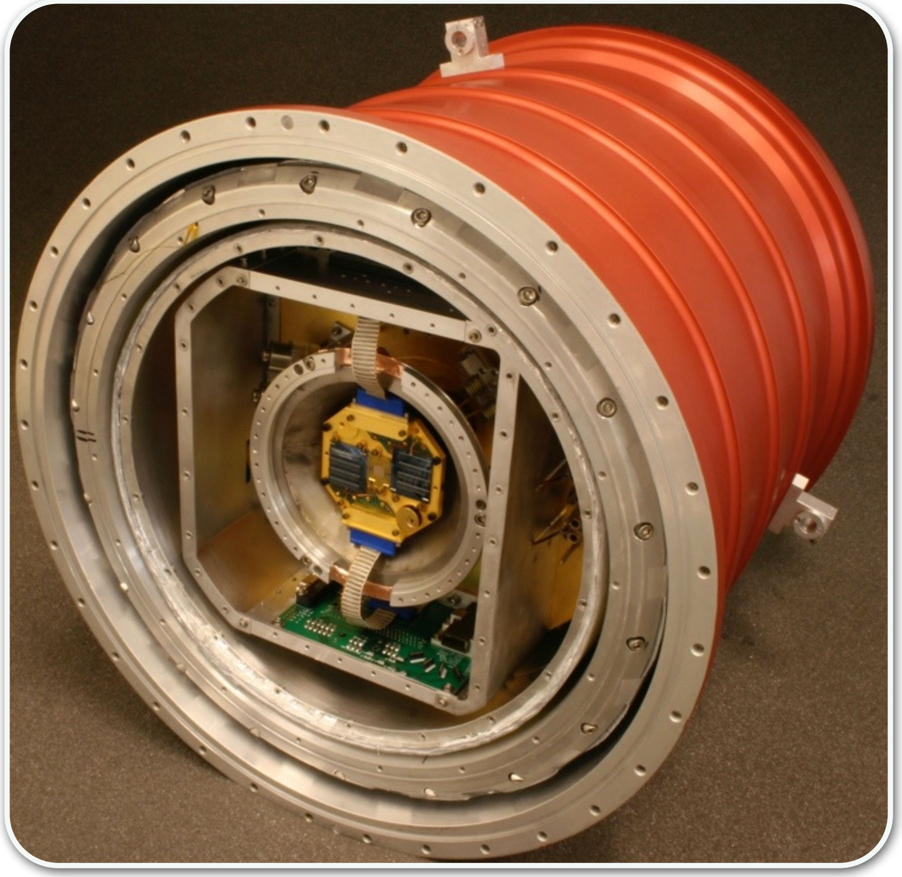
Outline

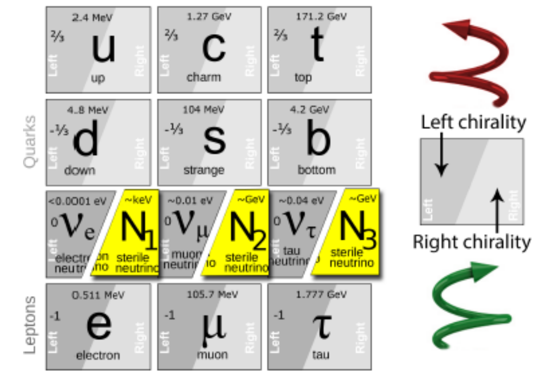


- 3.5 keV line
  - Detections
  - Non-detections
  - Status
- Astro-H X-ray Observatory
- XQC & Micro-X Sounding Rocket Payloads

Sterile Neutrinos

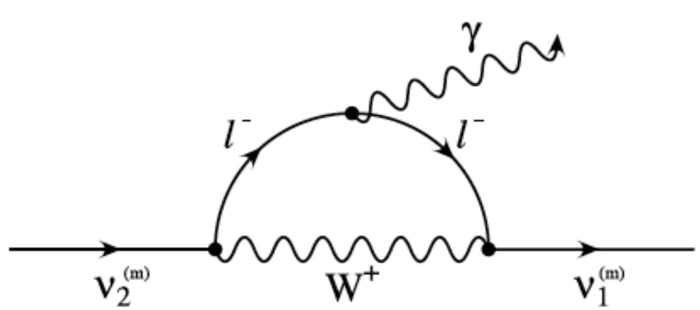
- Sterile neutrinos are a natural way of giving the known neutrino species mass. IF sterile neutrinos exist, and one of them has a mass between a few keV and 100 keV, it could constitute some or all of the dark matter.

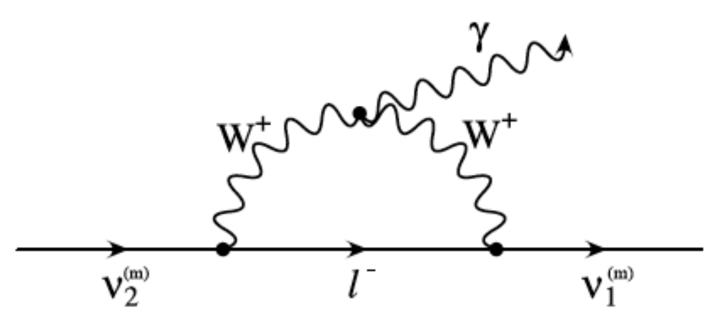
- Sterile neutrinos may decay to a photon and active neutrino via loop-suppressed processes.



$$\Gamma = \frac{9\alpha G_F^2 m_s^5 \sin^2 2\theta}{1024\pi^4}$$

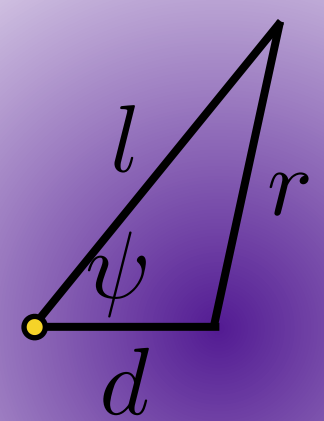
$$= (1.38 \times 10^{-29}\ \mathrm{s}^{-1}) \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

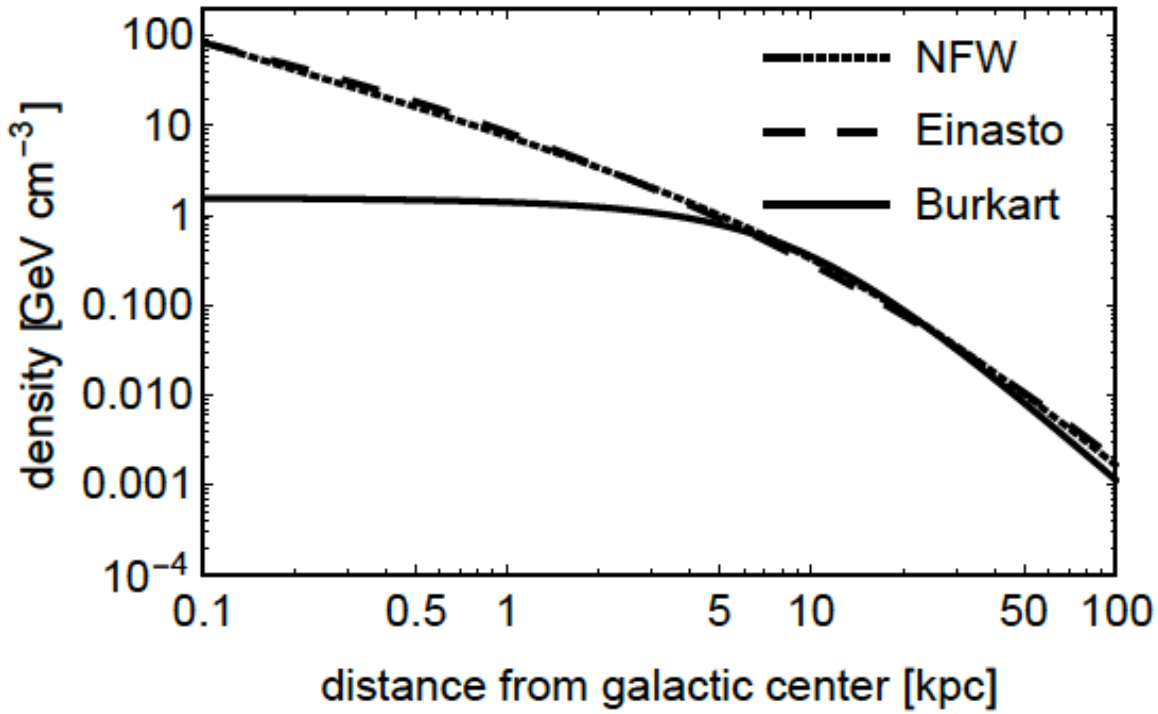




MW Sterile Neutrino Signal - FOV is important!

- The signal from sterile neutrino decay would be a line at half the energy of the sterile neutrino.





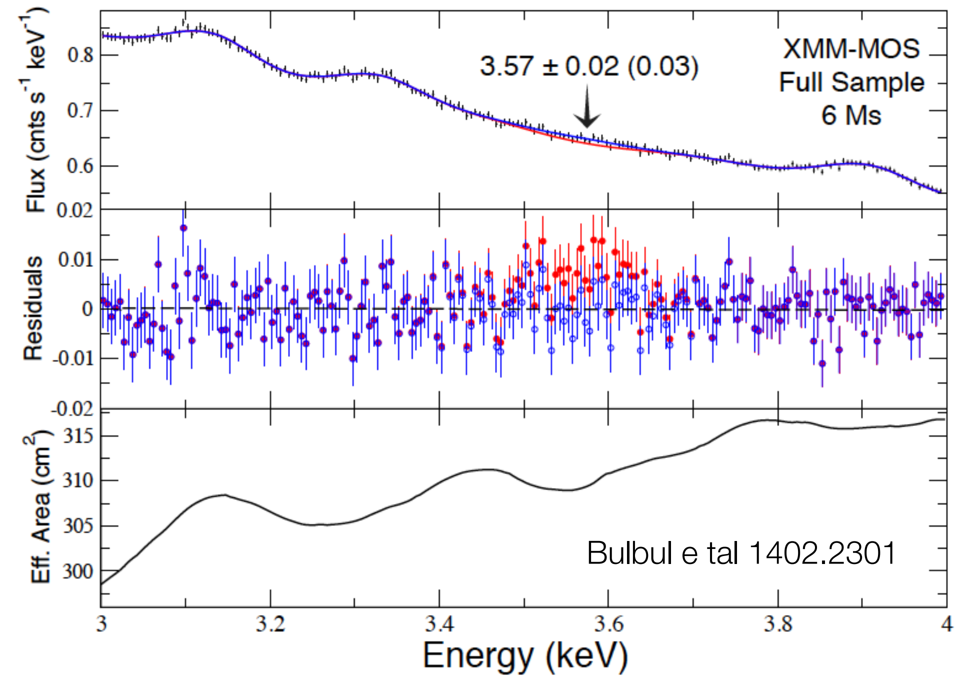
- The flux goes as the number of dark matter particles in your FOV. Estimates depend on assumed MW DM profile.

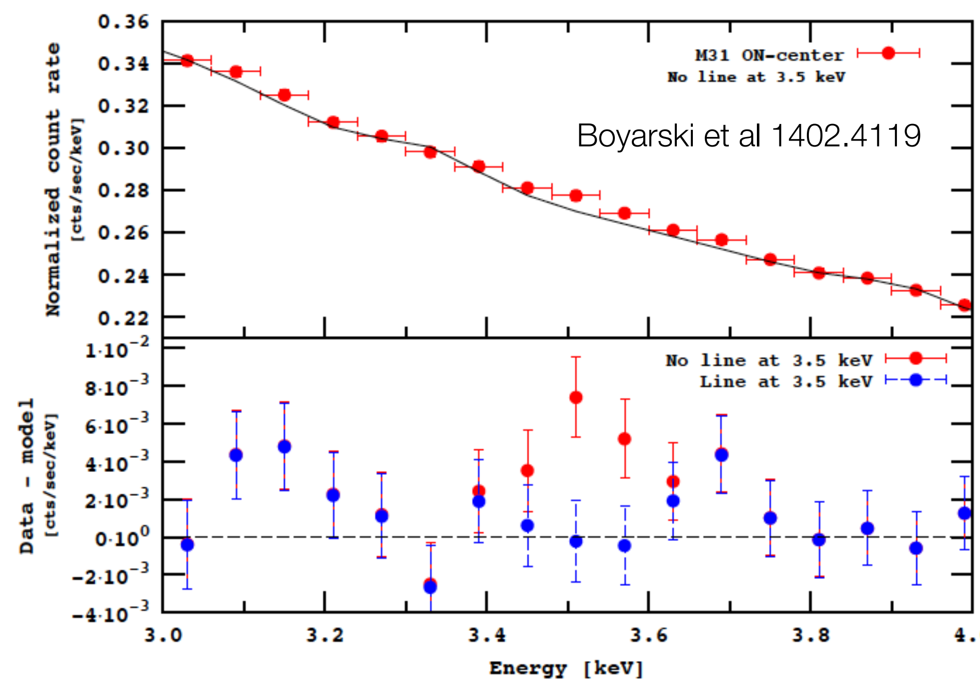
$$\mathcal{F} = \frac{\Gamma}{m_s}\frac{1}{4\pi}\int_{FOV}\int_0^{\infty}\rho(r(\ell,\psi))\;d\ell\,d\Omega$$

$$r(\ell,\psi) = \sqrt{\ell^2 + d^2 - 2\ell d\cos\psi}$$

The 3.5 keV Line

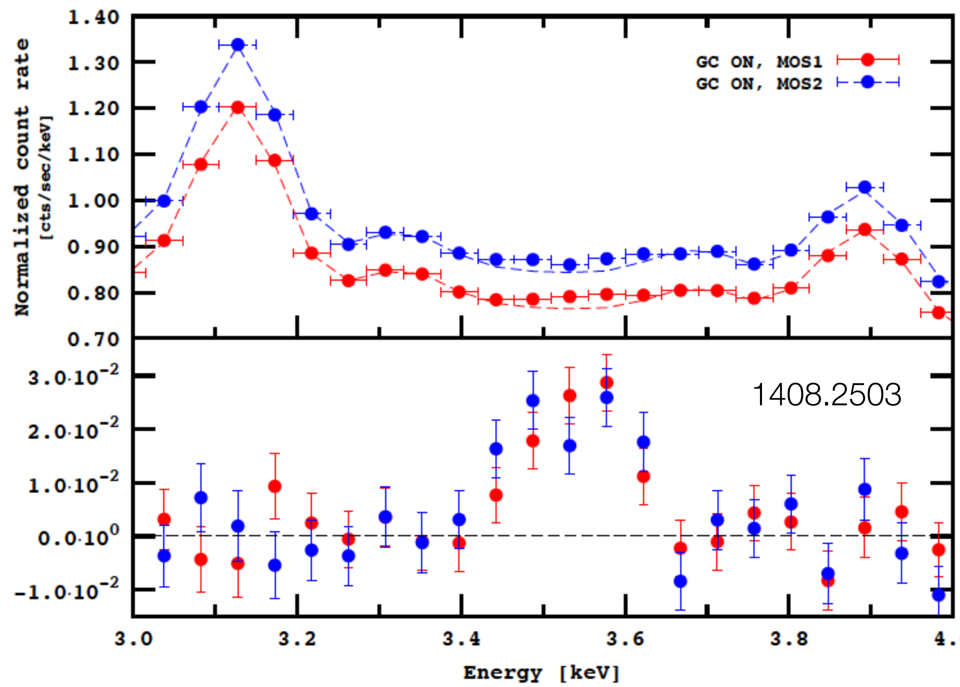
- 3.5 keV X-ray spectral line: initial discovery in XMM-Newton data by Bulbul et al (1402.2301) and Boyarsky et al (1402.4119), at >3σ significance.
- Bulbul et al studied 73 stacked galaxy clusters and found an excess at 3.56 keV consistent with a spectral line. They also find it in an analysis of the Perseus Cluster with Chandra.
- Boyarsky et al find an excess at 3.53 keV in their analysis of Perseus and the Andromeda Galaxy with XMM-Newton.

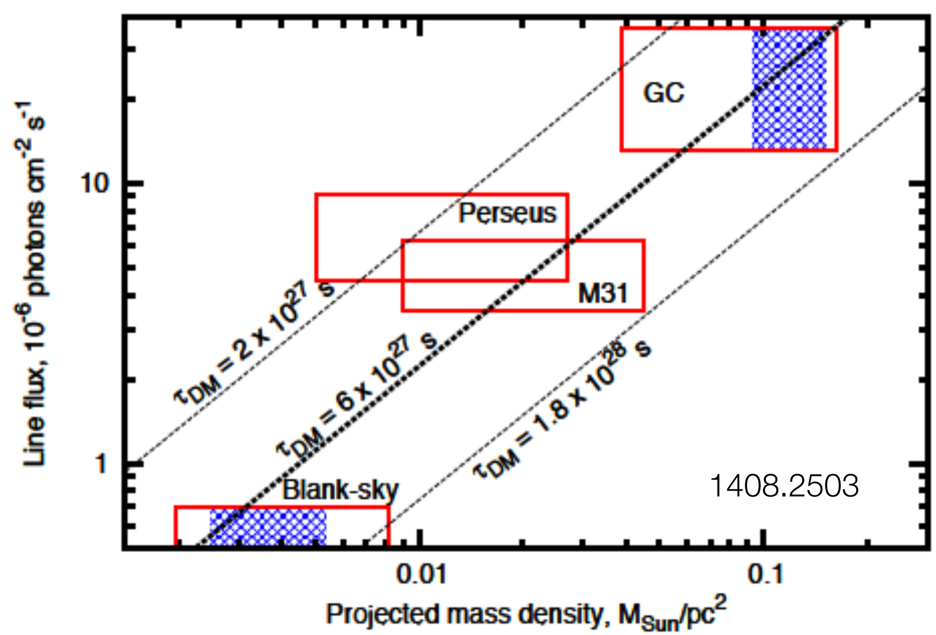




Milky Way Galactic Center

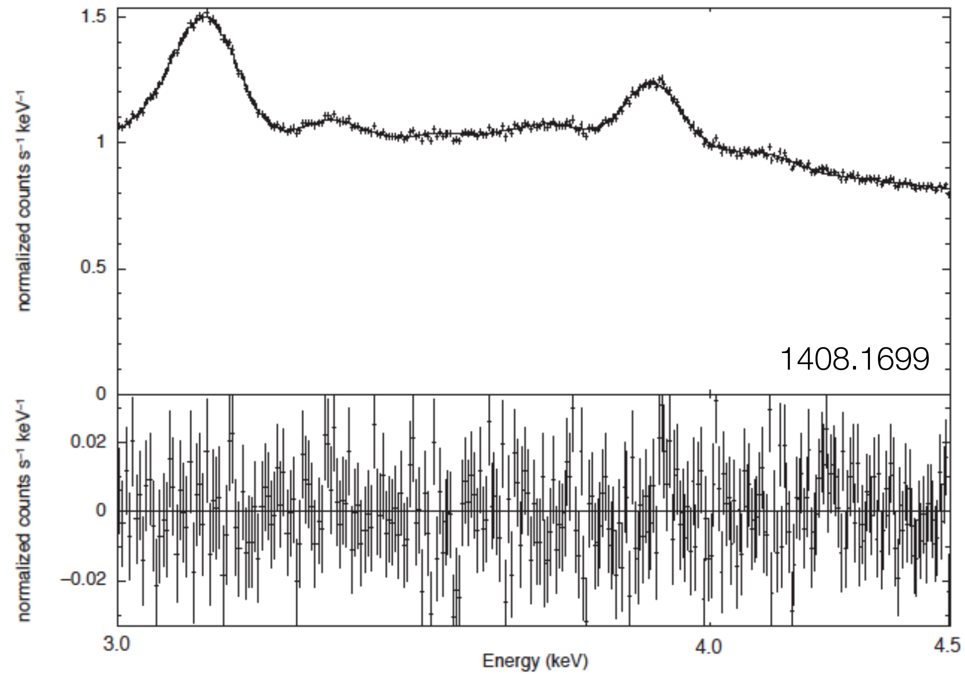
- Boyarsky et al (1408.2503) find a >5σ excess from the GC, with a 6.7σ significance when fitting the GC, Andromeda, and the Perseus Cluster, with consistent scaling of the claimed signal.
- However, an acceptable fit to the GC data is obtained when leaving K XVIII abundance as a free parameter.
- Given the instrumental resolution of XMM, the authors cannot distinguish between these two possibilities.





MW GC - Non detections

- Both Riemer-Sorensen (using Chandra 1405.7943) and Jeltma & Profumo (using XMM 1408.1699) analyze the GC and find no excess.
- Significant back and forth ensues about K XVIII and correct modeling of abundances and continuum.



Predicted MOS K XVIII Flux

kT	S XVI	Ar XVII (3.13 keV)	Ar XVII (3.69 keV)	Ca XIX	Ca XX/Ar XVII/K XVIII
0.8	5.0e-6	3.5e-6	5.4e-6	2.1e-5	4.4e-5
1.0	3.1e-6	4.3e-6	6.6e-6	2.3e-5	5.2e-5
2.0	1.5e-6	7.7e-6	1.2e-5	1.4e-5	3.9e-5
5.0	1.1e-6	2.0e-5	3.0e-5	1.1e-5	4.1e-6

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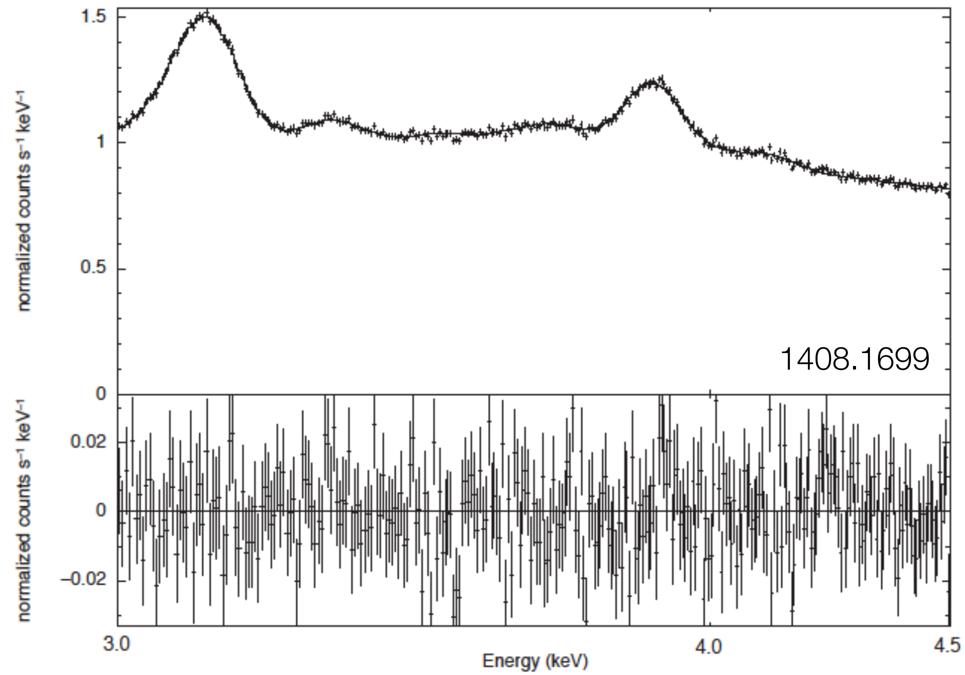


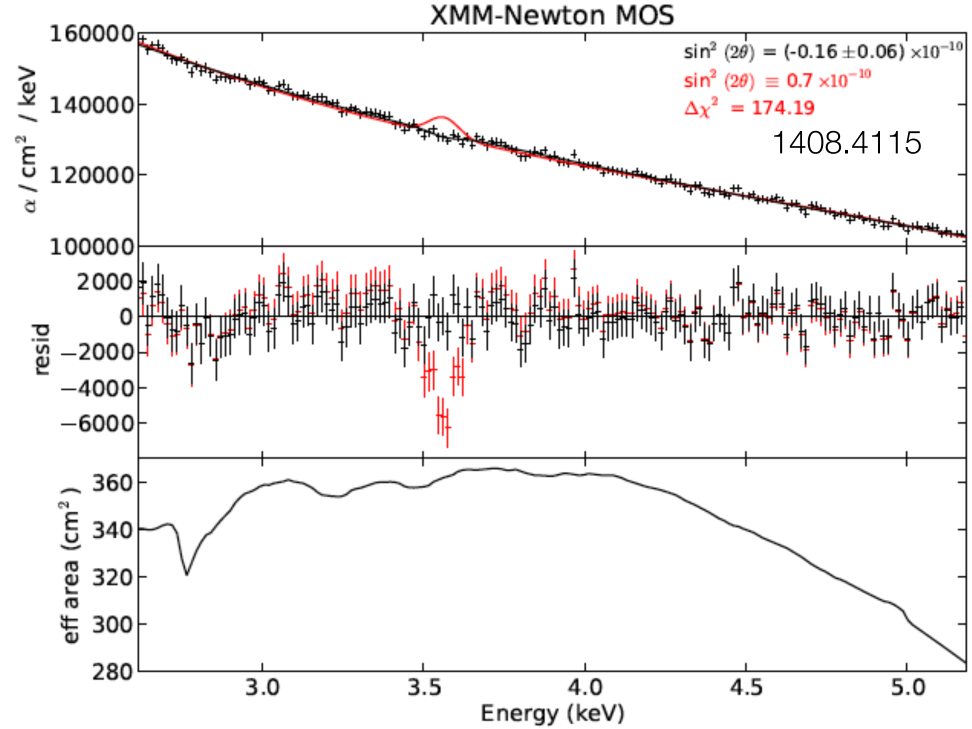
REVISED FLUXES (PH CM^{-2} S^{-1}) FOR JP TABLE 3 OF THE K XVIII $n = 2 \rightarrow 1$ TRIPLET BASED ON THE GALACTIC CENTER FLUXES PRESENTED IN JP TABLE 2, USING ATOMDB 2.0.2

1409.4143

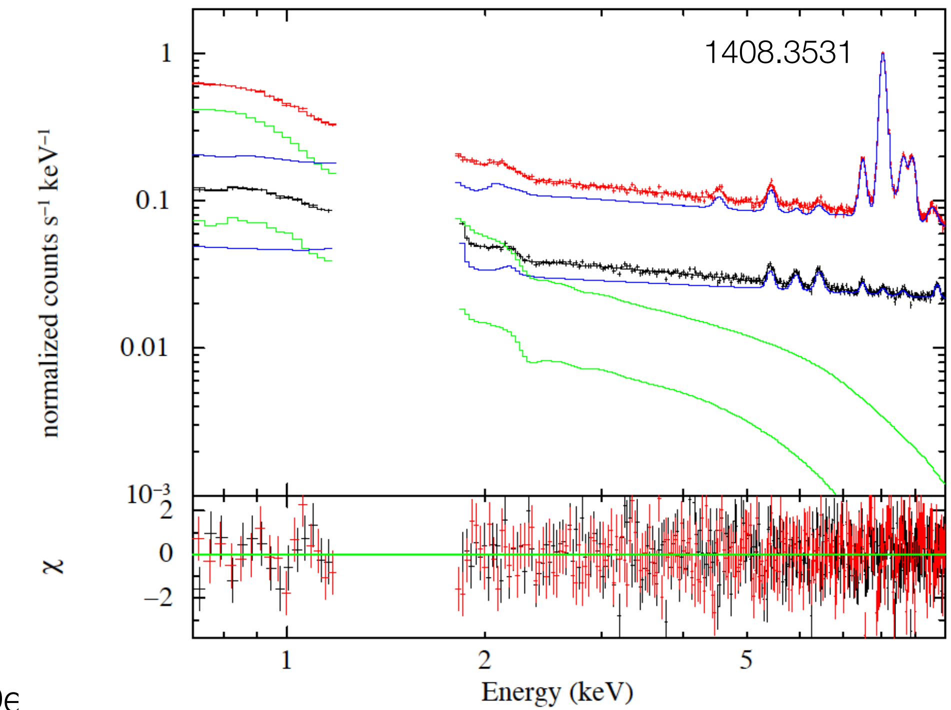
Te(keV)	S XVI	Ar XVII (3.13keV)	Ar XVII (3.69keV)	Ca XIX	Ca XX
Using our recommended lines					
0.8	6.1e-06	5.8e-06	1.8e-05	2.4e-05	2.6e-03
1.0	3.5e-06	6.8e-06	1.7e-05	2.0e-05	1.2e-03
2.0	1.8e-06	1.1e-05	1.9e-05	1.3e-05	2.6e-05
5.0	7.9e-07	1.8e-05	2.4e-05	7.2e-06	1.1e-06

Galaxies, Groups, and Dwarf Spheroidals

- Anderson et al 1408.4115 analyzed a large stacked sample of galaxies (81 with Chandra and 89 with XMM, with 15.0 and 14.6 Ms exposures), ruling out a 3.57 keV at 4.4σ and 11.8σ, respectively.

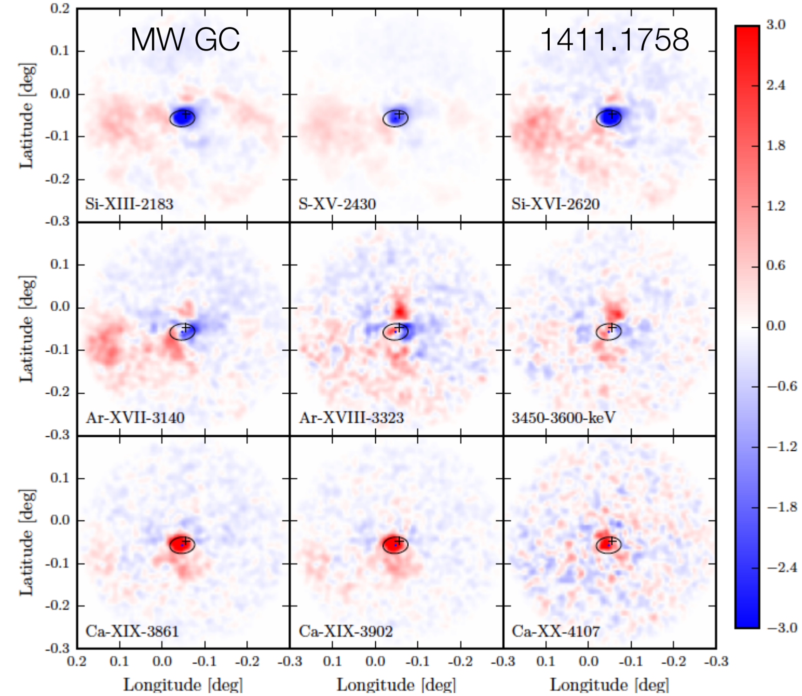


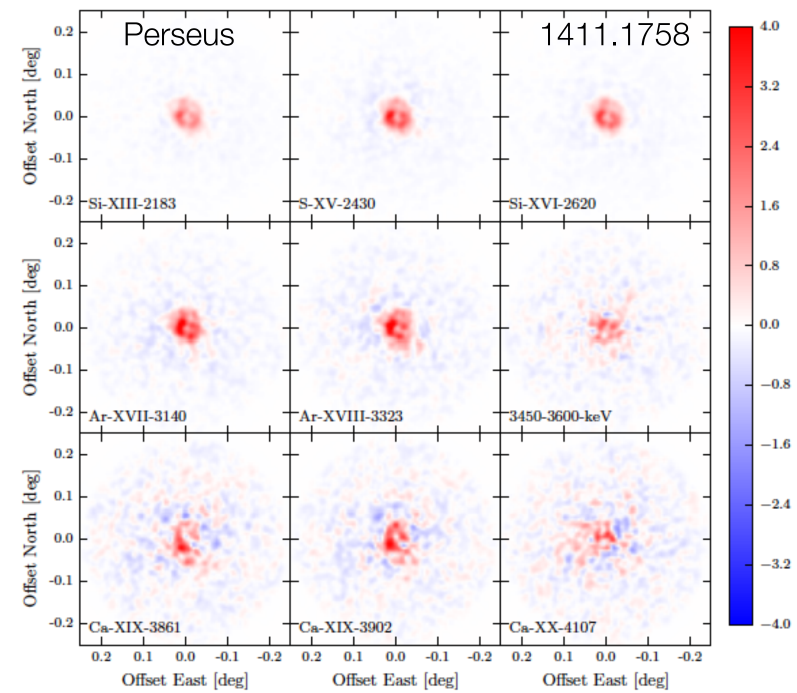
- Malyshev et al 1408.3531 looked at 8 dwarf spheroidal galaxies with XMM (0.6 Ms total exposure) and rule out a line at 3.5 keV at the 4.6σ level.



Morphological Studies

- Urban et al 1411.0050 use Suzaku data and find an excess at 3.51 keV in the Perseus Cluster. They analyze the morphology of the excess and determine that its radial profile is inconsistent with the expected dark matter model, and furthermore do not see the excess in the Coma, Virgo or Ophiuchus Clusters.
- Carlson et al 1411.1758 use XMM data of both the MW GC and Perseus Cluster. They find that the Galactic Center 3.5 keV line photons trace the morphology of atomic lines at comparable energy, and that the Perseus 3.5 keV photons are highly correlated with the cluster's cool core
- Tamura et al 1412.1869 use Suzaku to do a spectroscopic search in different annuli of the Perseus Cluster and find no evidence for a line.





Current Status of 3.5 keV line

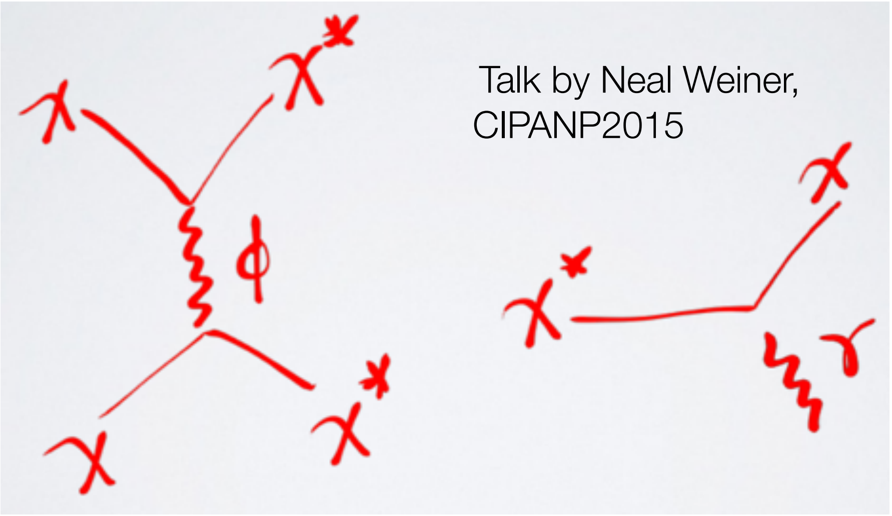
- Sterile neutrinos and other models where the signal is directly proportional to the dark matter density appear ruled out by the stacked galaxies and dwarf spheroidal results, modulo systematics in those analyses.
- Other dark matter models whose flux scales as ρ^n could explain the observations

Riemer-Sorenson (1405.7943, MW with Chandra data)
Jeltema & Profumo (1408.1699, MW)
Boyarsky et al (1408.2503, MW center
Malyshev et al (1408.3531, dwarf spheroidal galaxies)
Anderson et al (1408.4115, stacked galaxies with Chandra and XMM-Newton)
Urban et al (1411.0050, Suzaku)
Tamura et al (1412.1869, Suzaku)

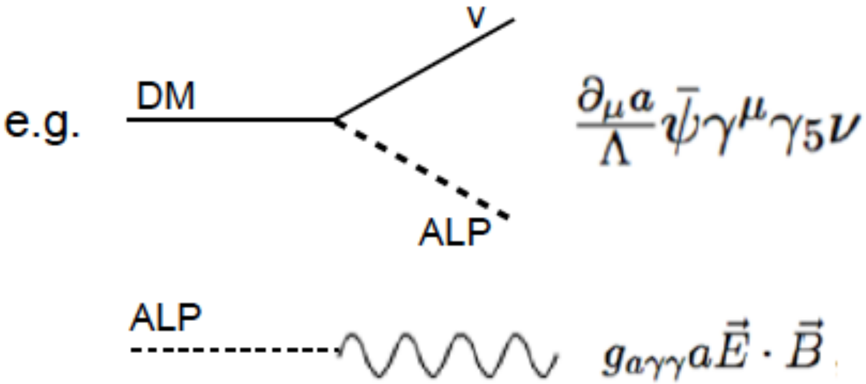
	XMM-Newton	Chandra	Suzaku
Stacked Clusters	+		
Perseus Cluster	+	+	±
Coma, Virgo, Ophiucus	+	-	-
Andromeda Galaxy	±		
Milky Way Galactic Center	+	-	
Stacked Galaxies	-	-	
Milky Way Dwarfs	-		

Alternate DM Explanations

- Exciting dark matter: (Finkbeiner & Weiner 1402.6671, Cline & Frey 1410.7766)
    - DM has a metastable excited state 3.5 keV above the ground state. This state is excited by DM-DM collisions, and subsequently decays producing a photon. Rate of excitation scales as density^2 x velocity dependence - much less constrained than just DM density, seems to allow compatibility with data.



- Another possibility is dark matter decay producing an axion-like particle, followed by conversion to an X-ray photon in the presence of magnetic fields (e.g. Conlon & Day 1404.7741). Can lead to bright signal in clusters, fainter in dwarfs and galaxies (Alvarez et al 1410.1867).



Slide from talk by Tracy Slater, Beyond WIMP conference

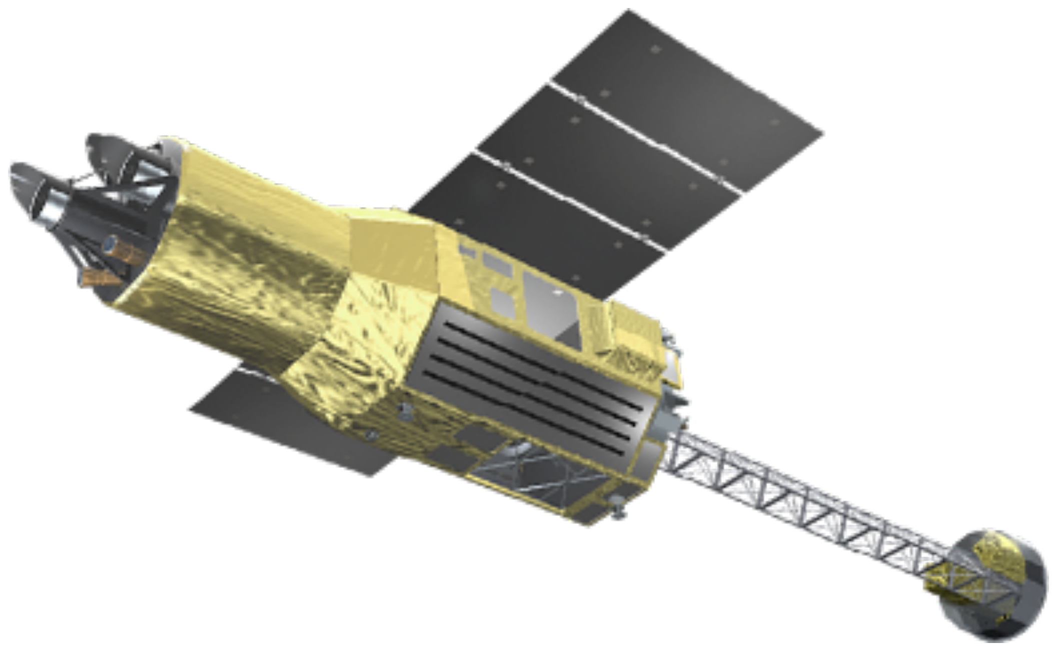
New Technology to the Rescue

- Whatever the fate of the 3.5 keV line, it seems clear we are reaching the limits of what is possible with existing observatories.
- X-ray observations in the 1-100 keV range continue to be fertile ground to search for new physics. New technology is needed to continue improving sensitivity.

Astro-H

Takayuki Tamura Talk at
Chalonge Meudon Workshop 2014
1412:1176
1412.1356

- Astro-H will launch in 2016 with a 7 eV FWHM energy resolution microcalorimeter and a 3' x 3' FOV.



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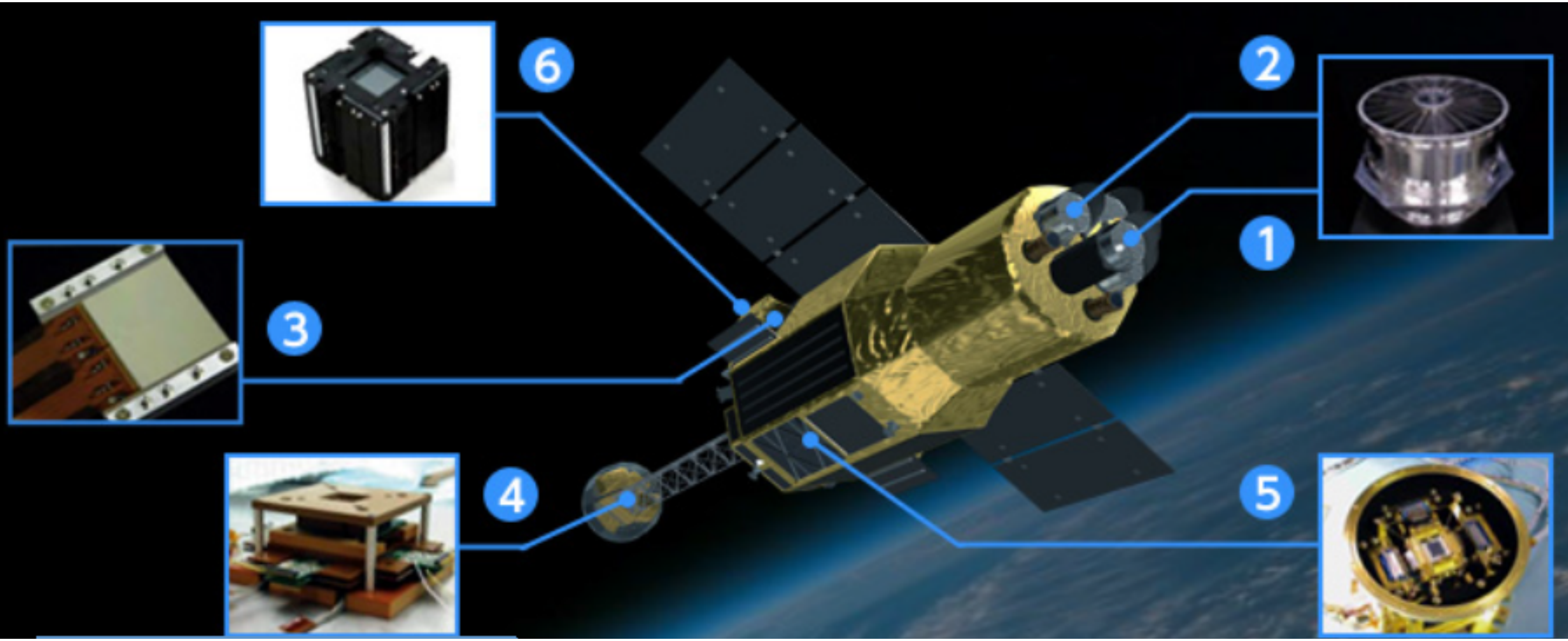
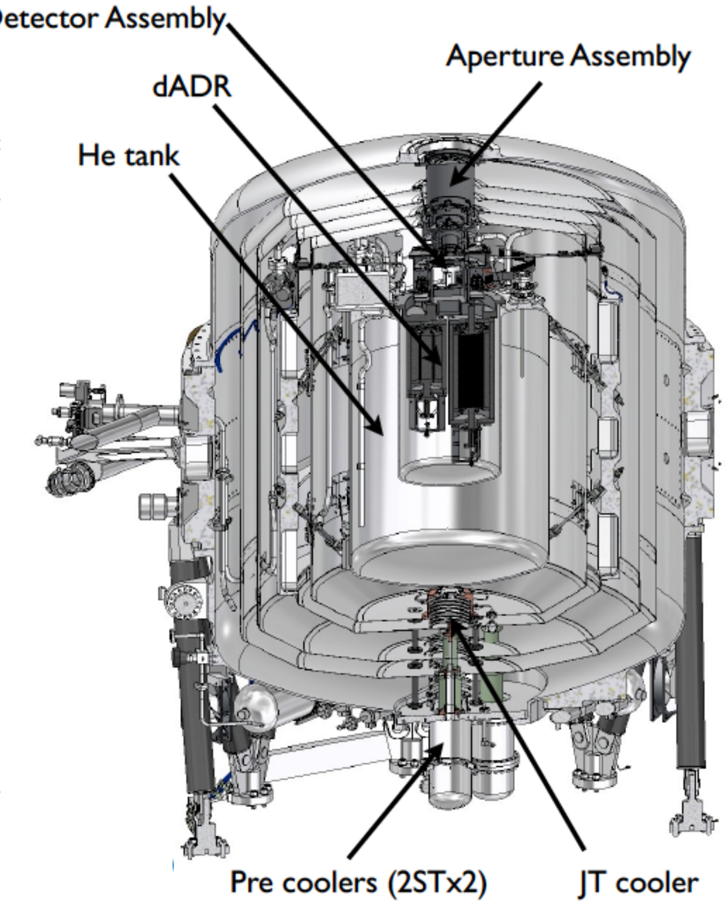


Astro-H Soft X-ray Spectrometer (SXS)

Table 1. *ASTRO-H* SXS key requirments

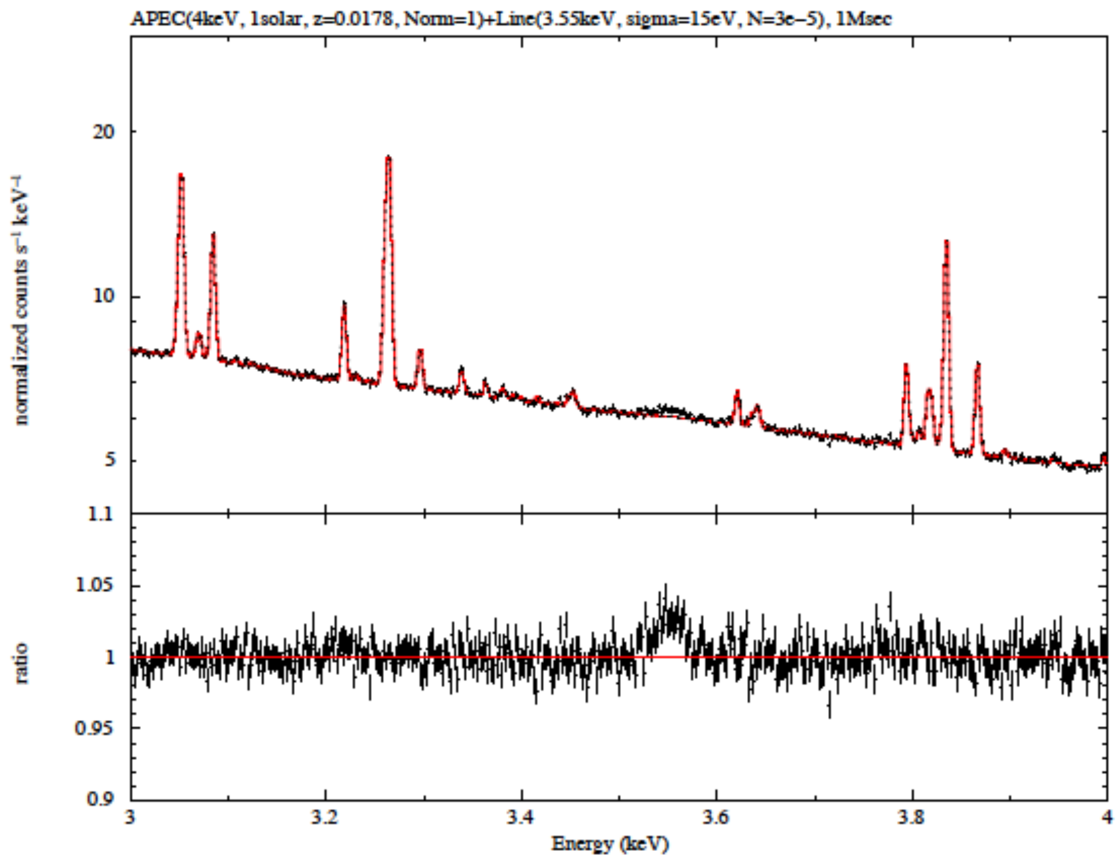
	Requirement	Goal
Energy range	0.3 - 12 keV	
Effective area at 1 keV	160 cm^2	
Effective area at 6 keV	210 cm^2	
Energy resolution	7 eV	4 eV
Array format	6×6	
Field of view	$2.9' \times 2.9'$	
Angula resolution	1.7'(HPD)	1.3' (HPD)
Lifetime	3 years	5 years
Time assignment resolution	80 μs	
Maximum counting rate	150 c s^{-1} $pixel^{-1}$	
Energy-scale calibration accuracy	2 eV	1 eV
Line-spread-function calibration accuracy	2 eV	1 eV



- The FOV limits its ability to look for the all-sky signal expected from sterile neutrino decay in the Milky Way (although it will certainly look!)

- Extragalactic sources from galaxy clusters to dwarf spheroidals are better fits to its FOV.

Astro-X SXS Microcalorimeter Perseus Simulation



A simulation of 1Msec observation with a dark matter line at 3.55keV.
We assume a ICM thermal emission of kT=4keV, 0.7solar, z=0.0178, and a X-ray flux of the Perseus center. No turbulent line broadening is assumed. For the dark matter emission, line broadening of a FWHM of 35eV by σ=1300km/ velocity dispersion is assumed. Line flux is 3×10^{-5} ph/s/cm^2 (Bulbul+2014).The model in red assumes no DM line.

Sounding Rocket Payloads for Sterile Neutrino Searches

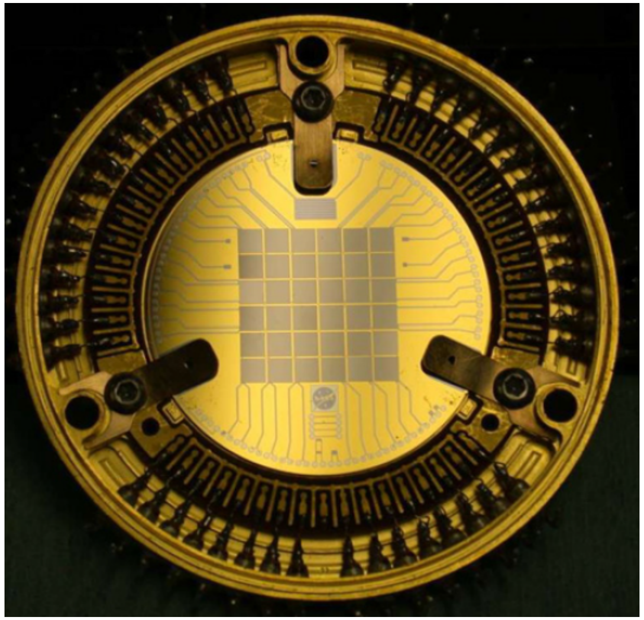
PRELIMINARY

Sounding Rocket Payloads

- 300 seconds of on-target data above 169 km
- High resolution X-ray microcalorimeter with ~1cm^2 area and large ~steradian FOV
- Flights from White Sands Missile Range in New Mexico and Woomera Range in Australia

The XQC Rocket Payload

- Mature flight system flown 6 times between 1995 and 2014
- Si Thermistor Microcalorimeter array with 36 pixels, each with a 2mm x 2mm x 0.96µm HgTe absorber on a 14µm Si substrate
- Baseline energy resolution is 11 eV FWHM, 23 eV FWHM at 3.3 keV.
- 1 steradian FOV ~ 1900 arcmin radius



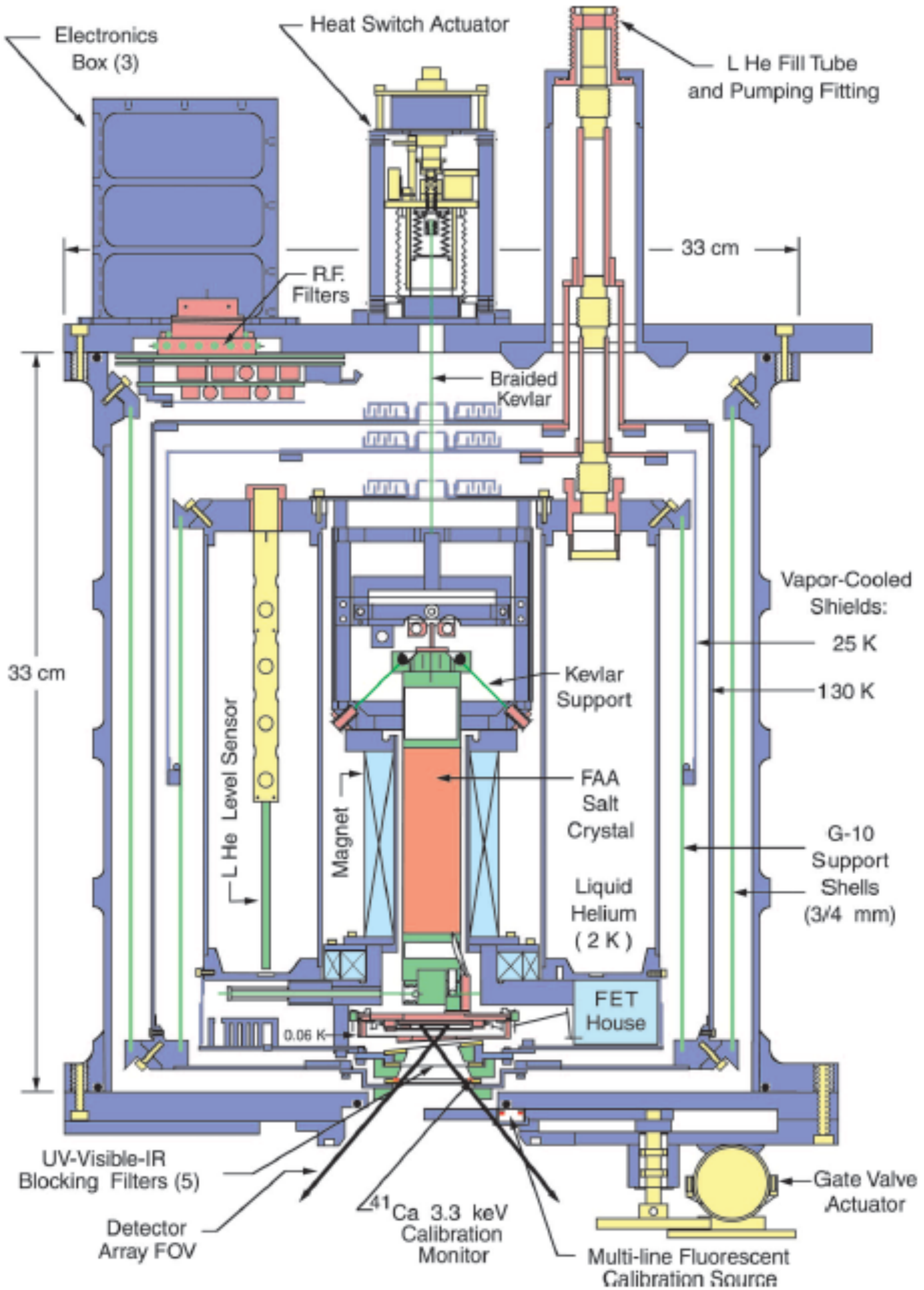
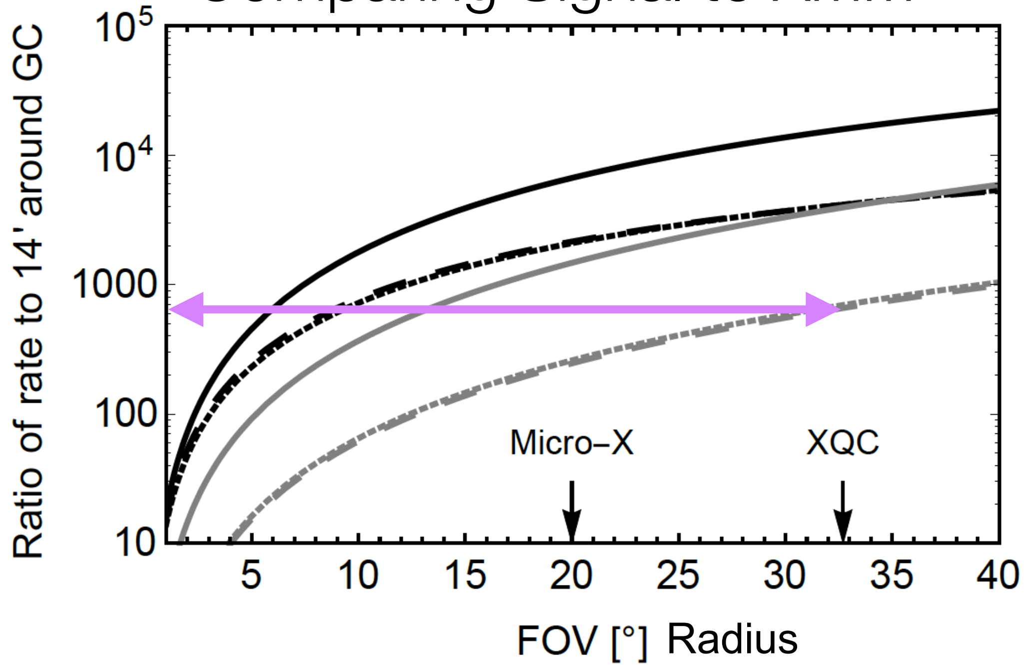


Fig. 1.—Cross section of sounding rocket cryostat. Total weight is 27 kg with electronics and vibration mounts.

Analysis of XQC Data

- Analyzed data from 5th flight of XQC, which flew Nov 6 2011.
- 1 steradian FOV centered on Galatic coords l=165, b=-5, close to Galactic anti-center.
- About 300 seconds of on-target data were acquired at altitudes above 160 km, of which 200 s of data on 29 pixels were analyzed. After quality cuts, the effective exposure is 106 s.
- Future analysis of entire XQC data set from all flights will increase the exposure by a factor of about 5.

Comparing Signal to XMM

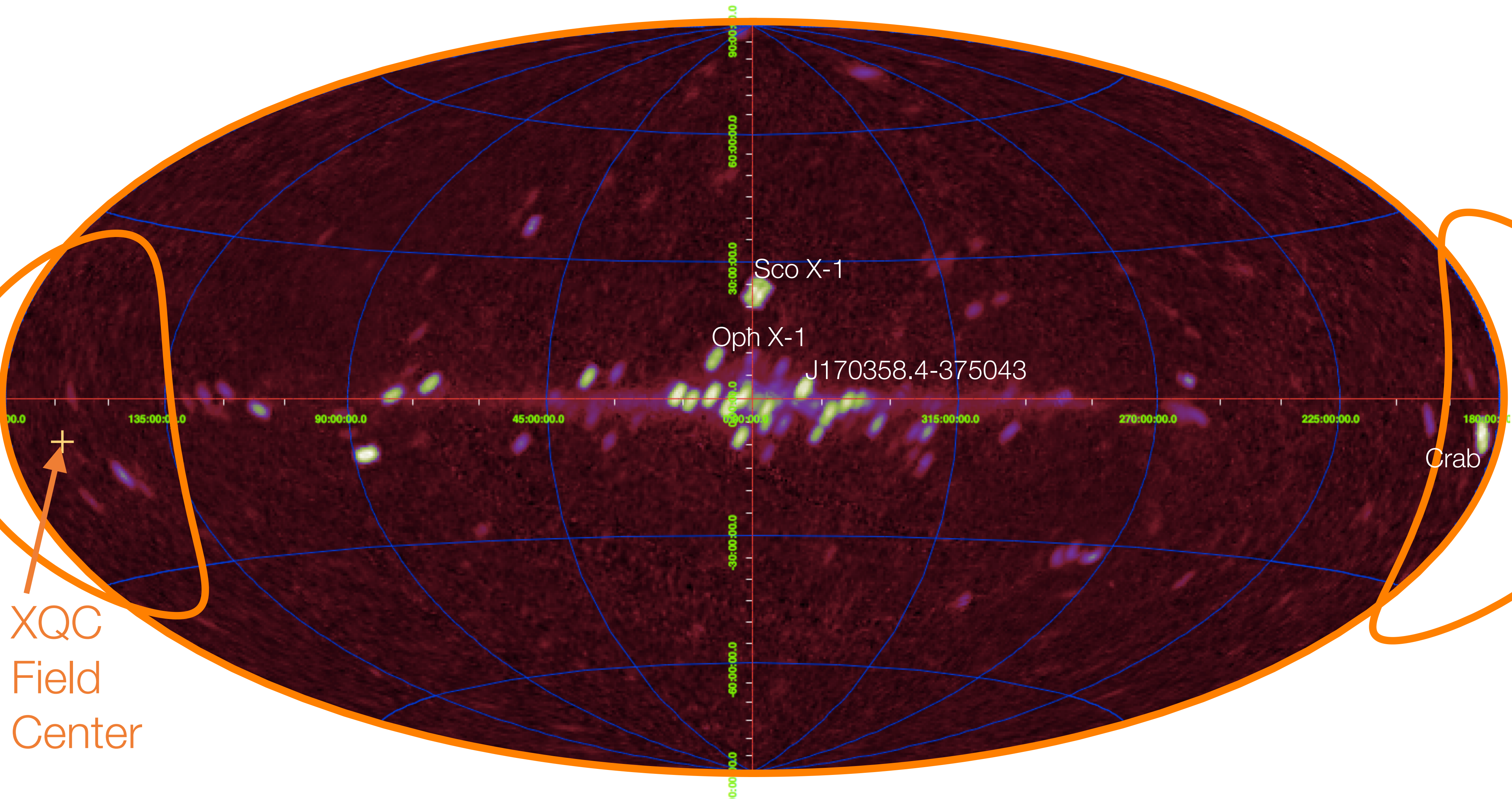


Dotted: NFW
Dashed: Einasto
Solid: Burkart

Black: Galactic Center
Gray: XQC Field

Einstein (HEAO-2) 2-9 keV All-Sky Map

1978-1982



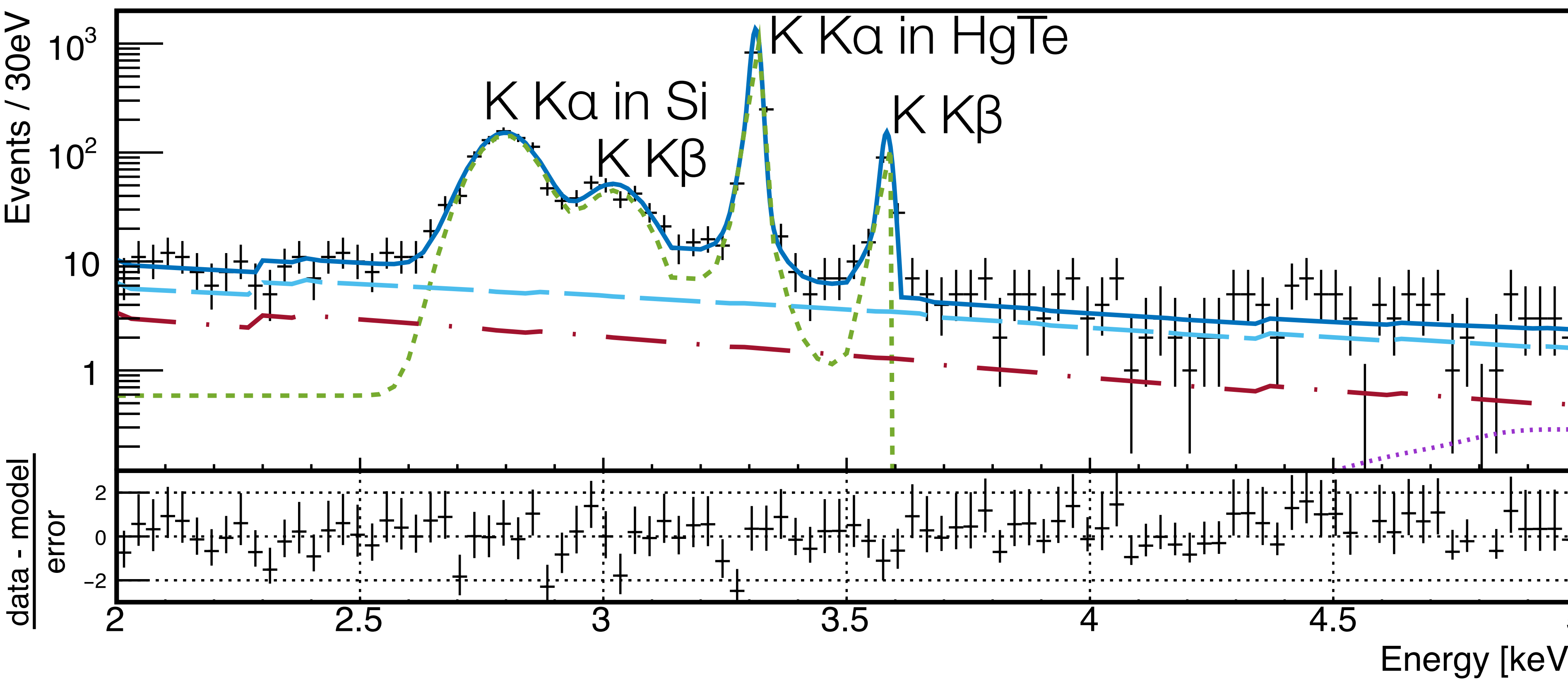
Fit to XQC Data

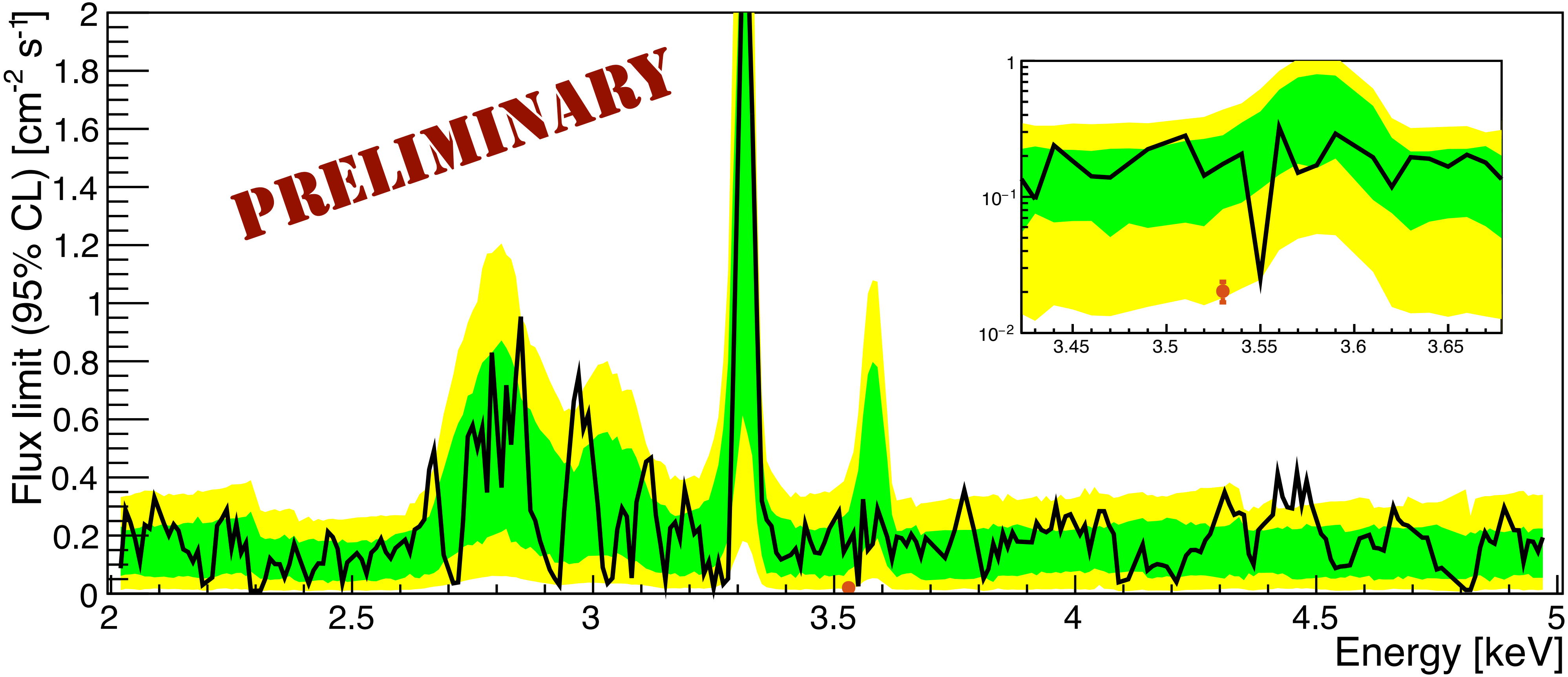
Diffuse X-ray Background ((Hickox & Markevitch 2006)

Crab (Mori et al 2004)

Calibration Source (model from pre-flight calibration data)

Cosmic Rays (GEANT4 simulation)

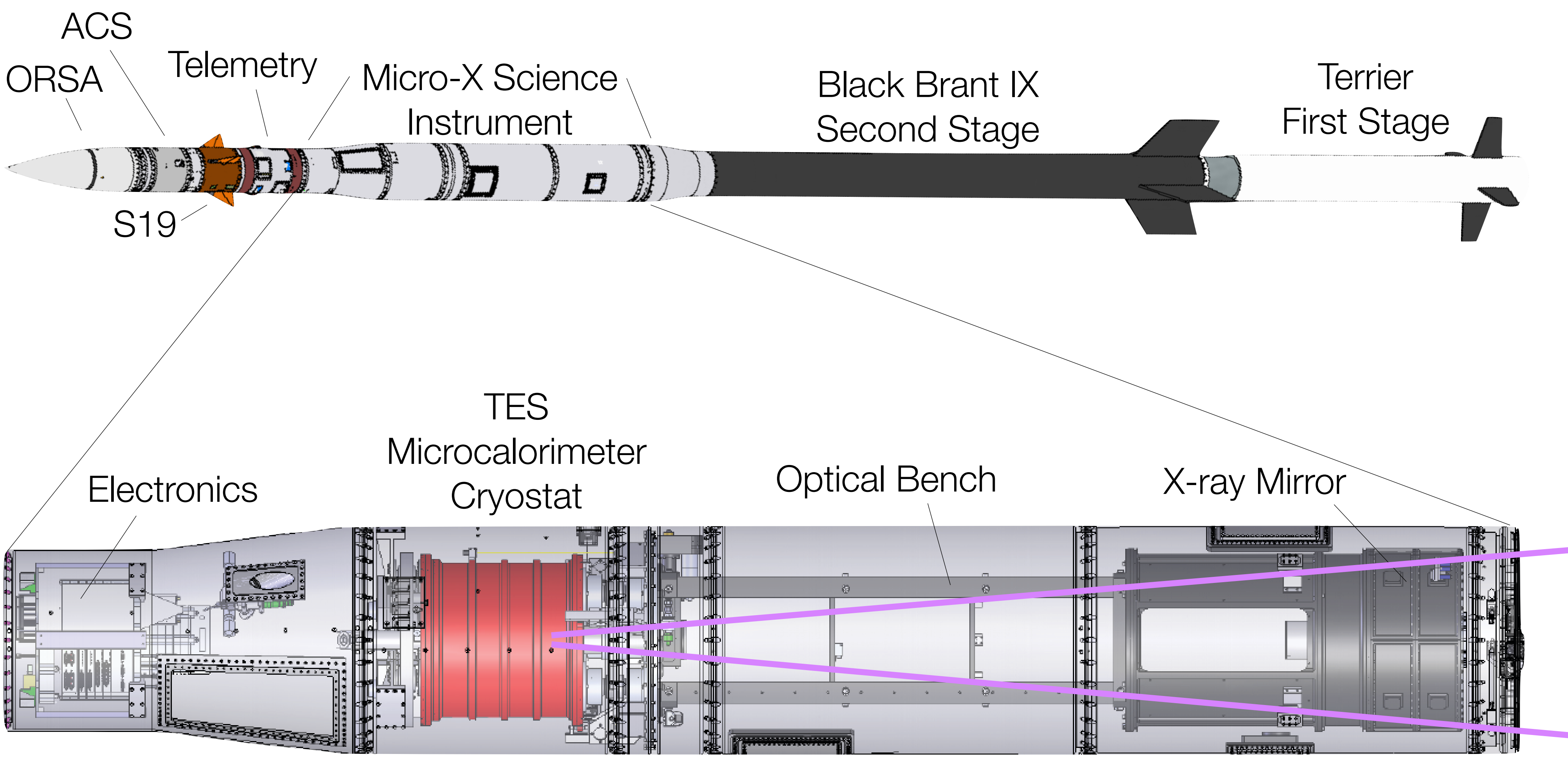




- Use extended unbinned maximum likelihood to set an upper limit for an unidentified line above the background model
- At 3.53 keV, we set an upper limit on the flux of an unidentified line of 0.17 cnts cm^{-2} s^{-1} at 95% CL.
- Not sensitive enough to rule out Boyarski's MW detection claim… will analyze existing archival data to gain a factor of around 5 in exposure

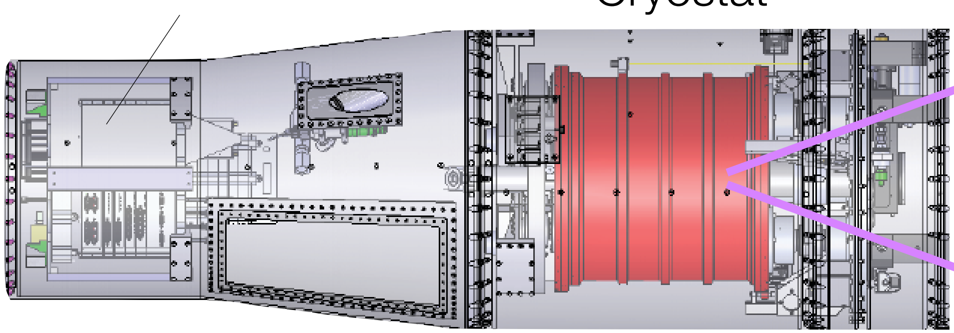
Future Sounding Rocket Observations

The Micro-X Sounding Rocket



The Micro-X Sounding Rocket

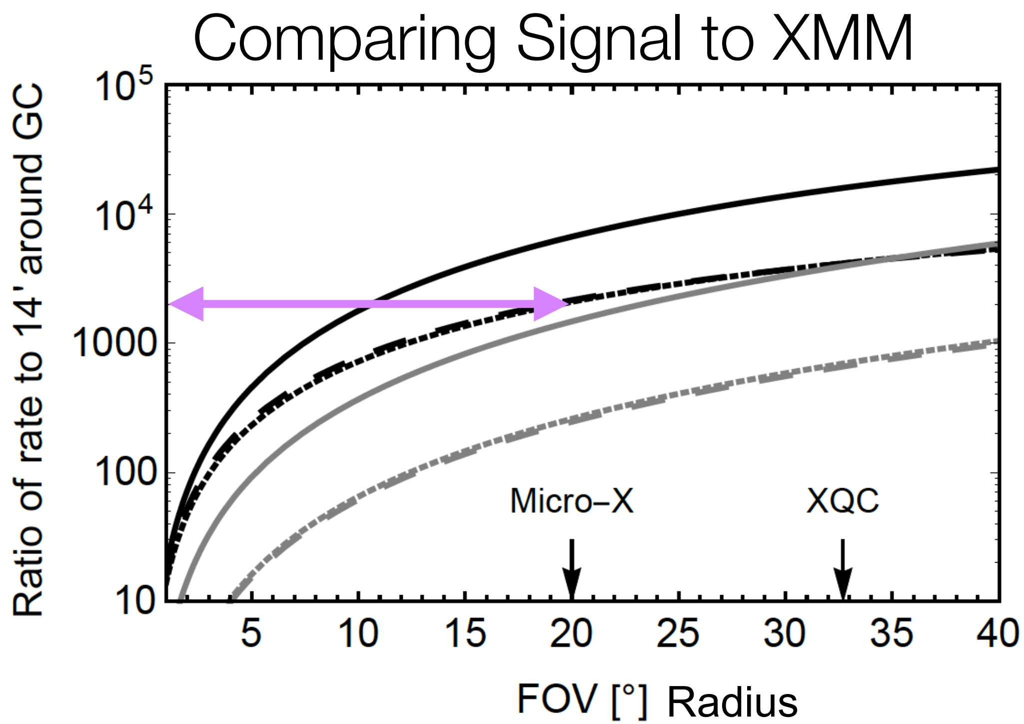
- Payload under development. First flight next year!
- TES Microcalorimeter array with 128 pixels, each with a 0.9mm x 0.9mm x (3μm Bi + 0.7μm Au) absorber
- Baseline energy resolution is 3-4 eV FWHM, flat out to 6-7 keV.
- 0.38 steradian FOV ~ 1200 arcmin radius, expect to increase to 1 sr in the future.



- For sterile neutrino searches, we will fly the payload without the mirror to obtain a large FOV and thus greater grasp:
    - With mirror, grasp = 38 cm^2 deg^2
    - Without mirror, grasp = 1256 cm^2 deg^2

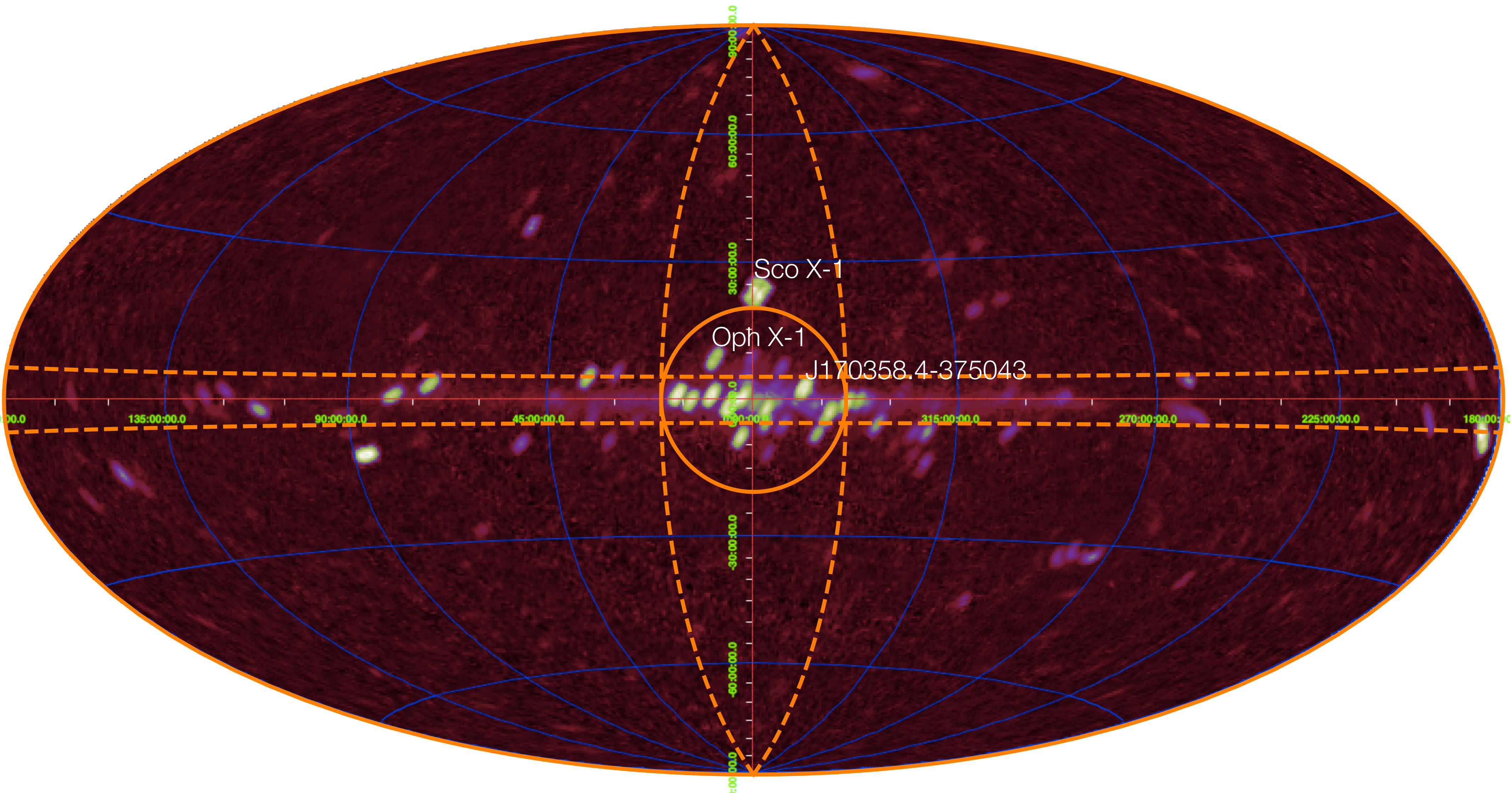
Comparing Micro-X to XMM

- Using the Boyarski et al XMM claimed signal from the GC as a benchmark, we scale to the Micro-X FOV to estimate signal and background from a Micro-X observation.
- Using NFW, Micro-X signal is ~2000 times higher than XMM observation.



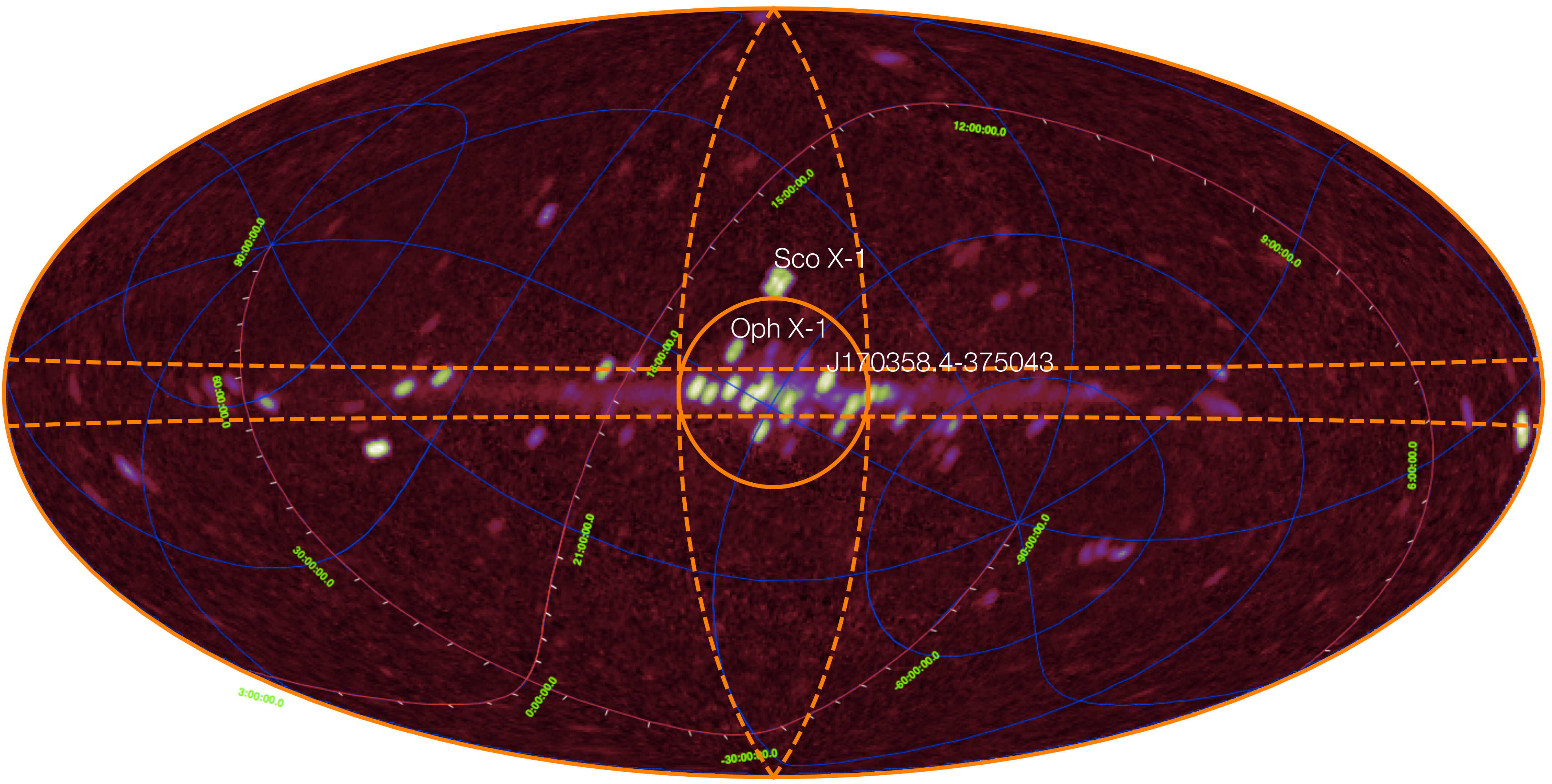
reference flux (in 14' of GC)	$2.9 \times 10^{-5}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
scaled flux (in 20° of GC)	$6.1 \times 10^{-2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
effective area at 3.55 keV	$1\ \mathrm{cm}^2$
exposure time	300 s
resolution (FWHM)	3 eV
signal events (in 20° of GC) Radius	18.2
bg. rate at 3.55 keV (see §4.1)	$4.5\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{keV}^{-1}$
bg. events in signal window	6.7
median signal significance	$5.6\ \sigma$

FOV for Micro-X GC Observation



Einstein 2-9 keV All-Sky Map

GC Observation from Australia in 2017

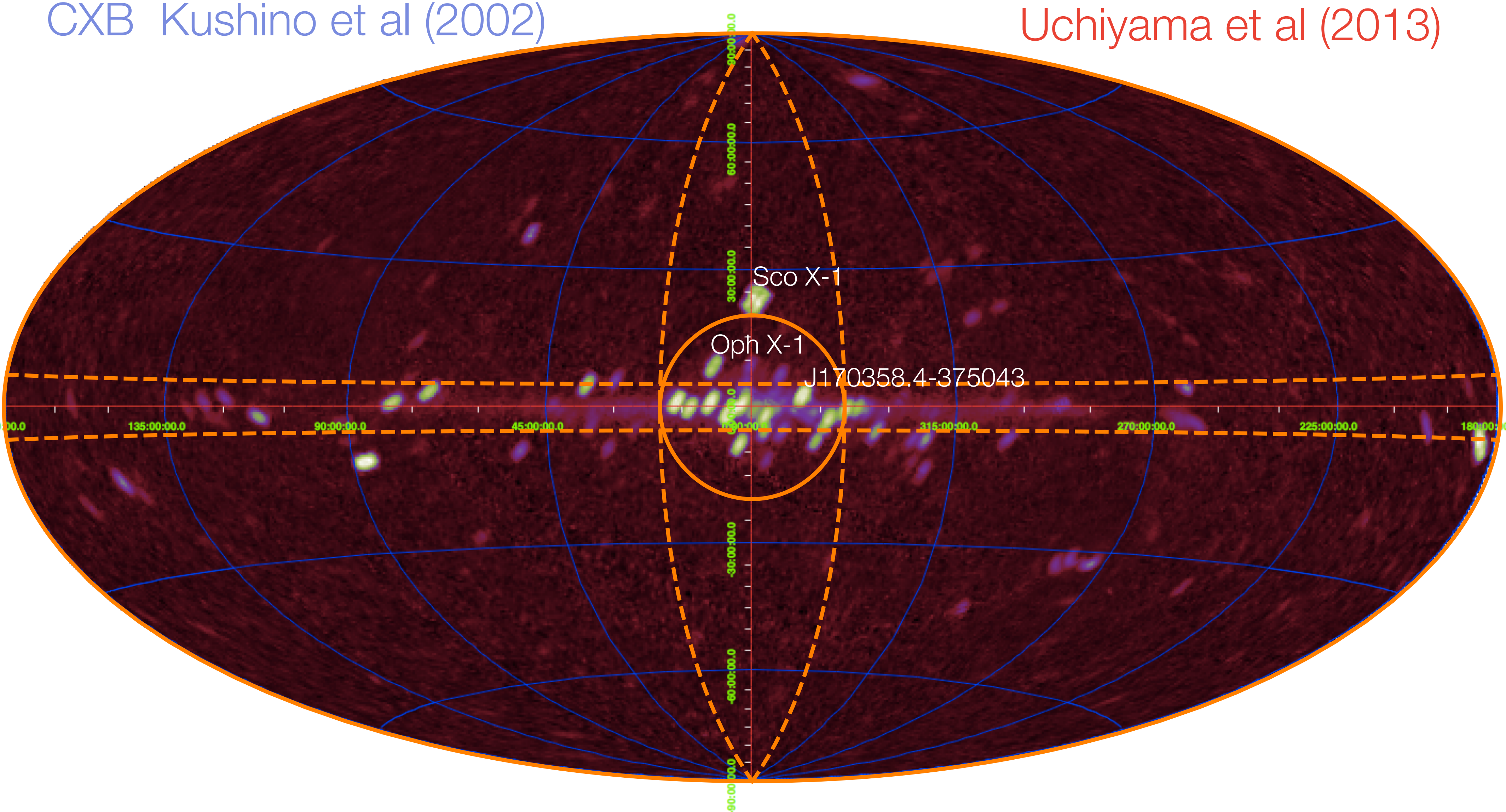


Einstein 2-9 keV All-Sky Map

Background Estimates for Micro-X GC Observation

LMXBs
CXB Kushino et al (2002)

Galactic Thermal Model
Uchiyama et al (2013)



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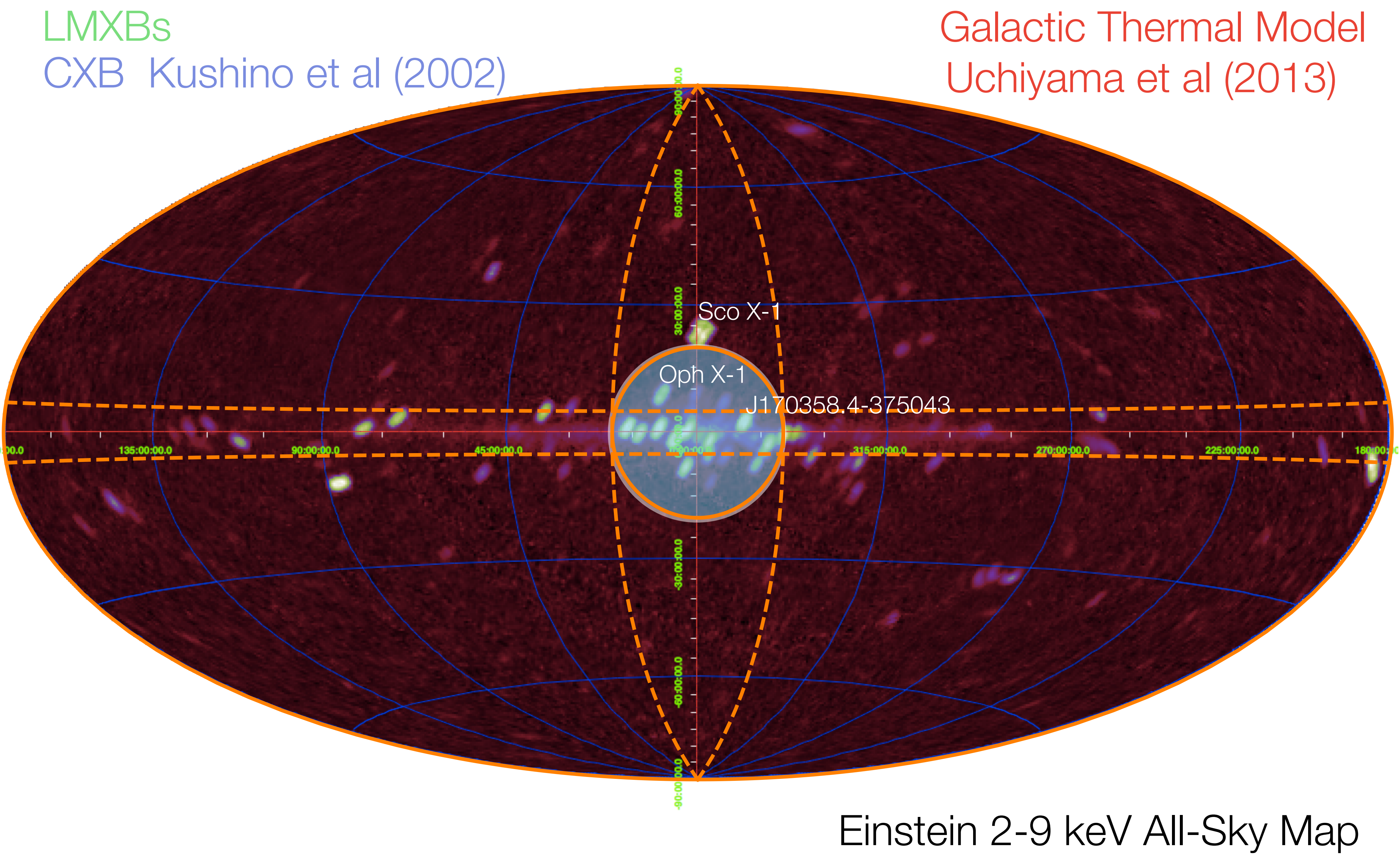

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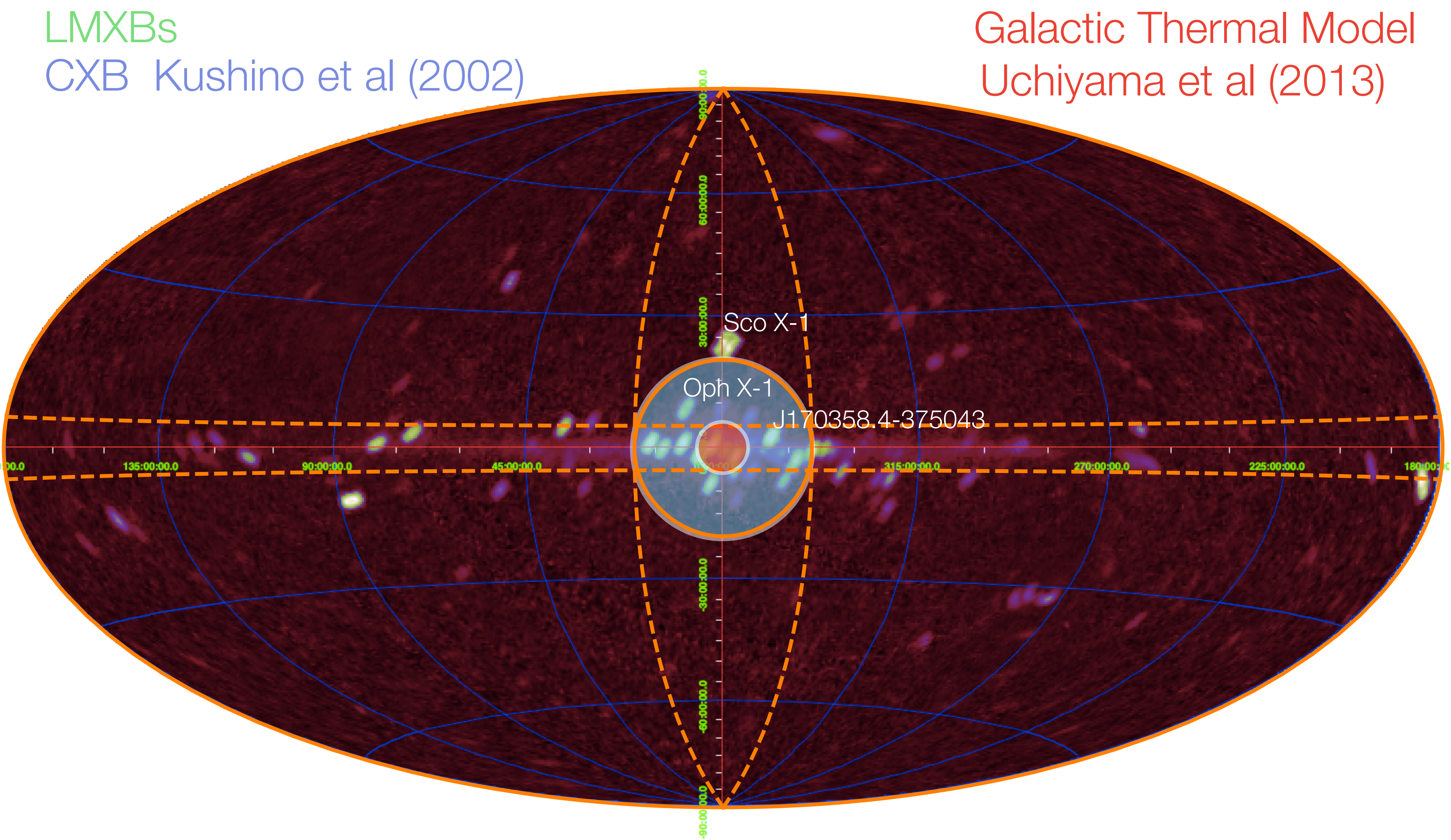

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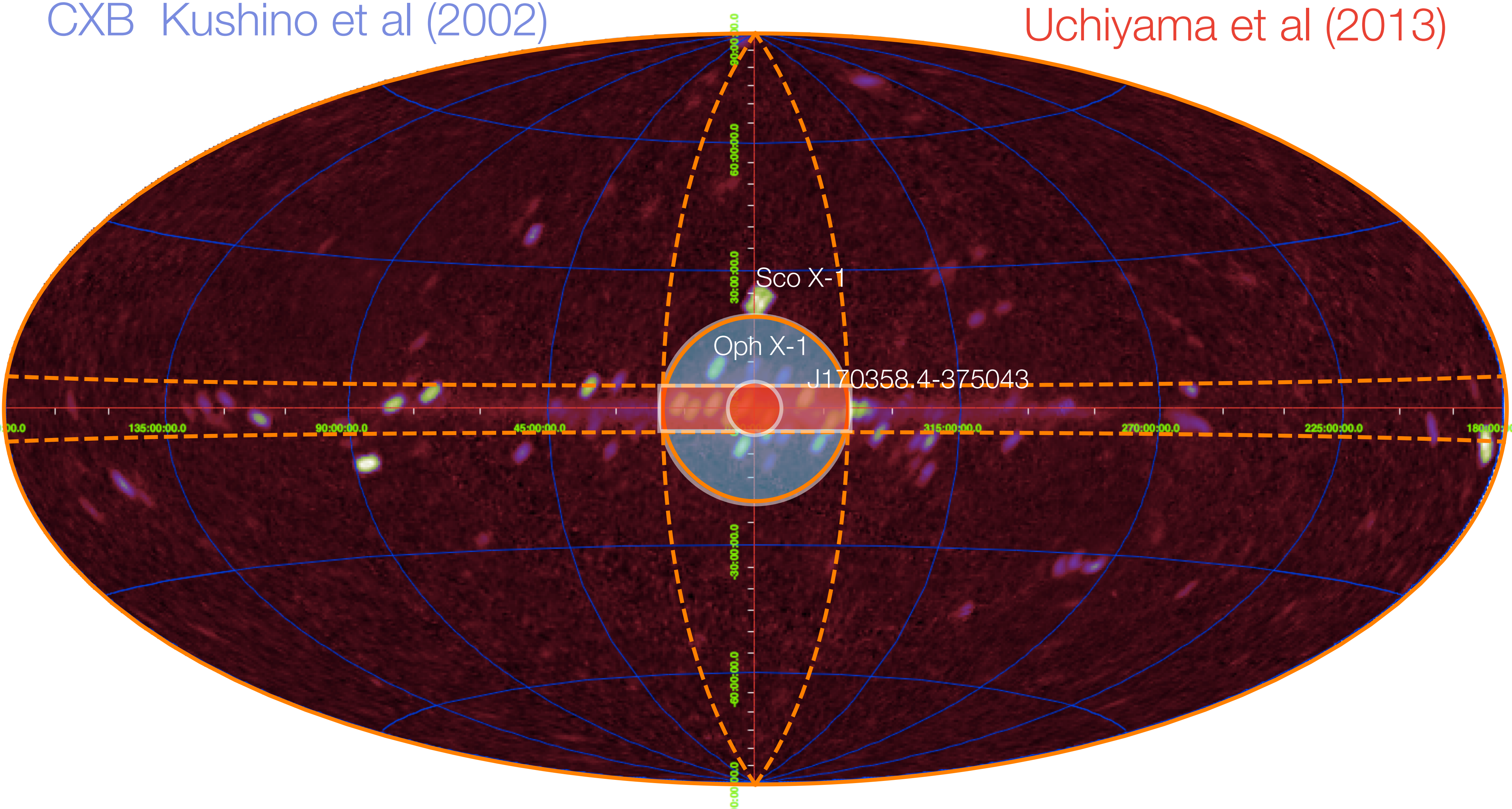

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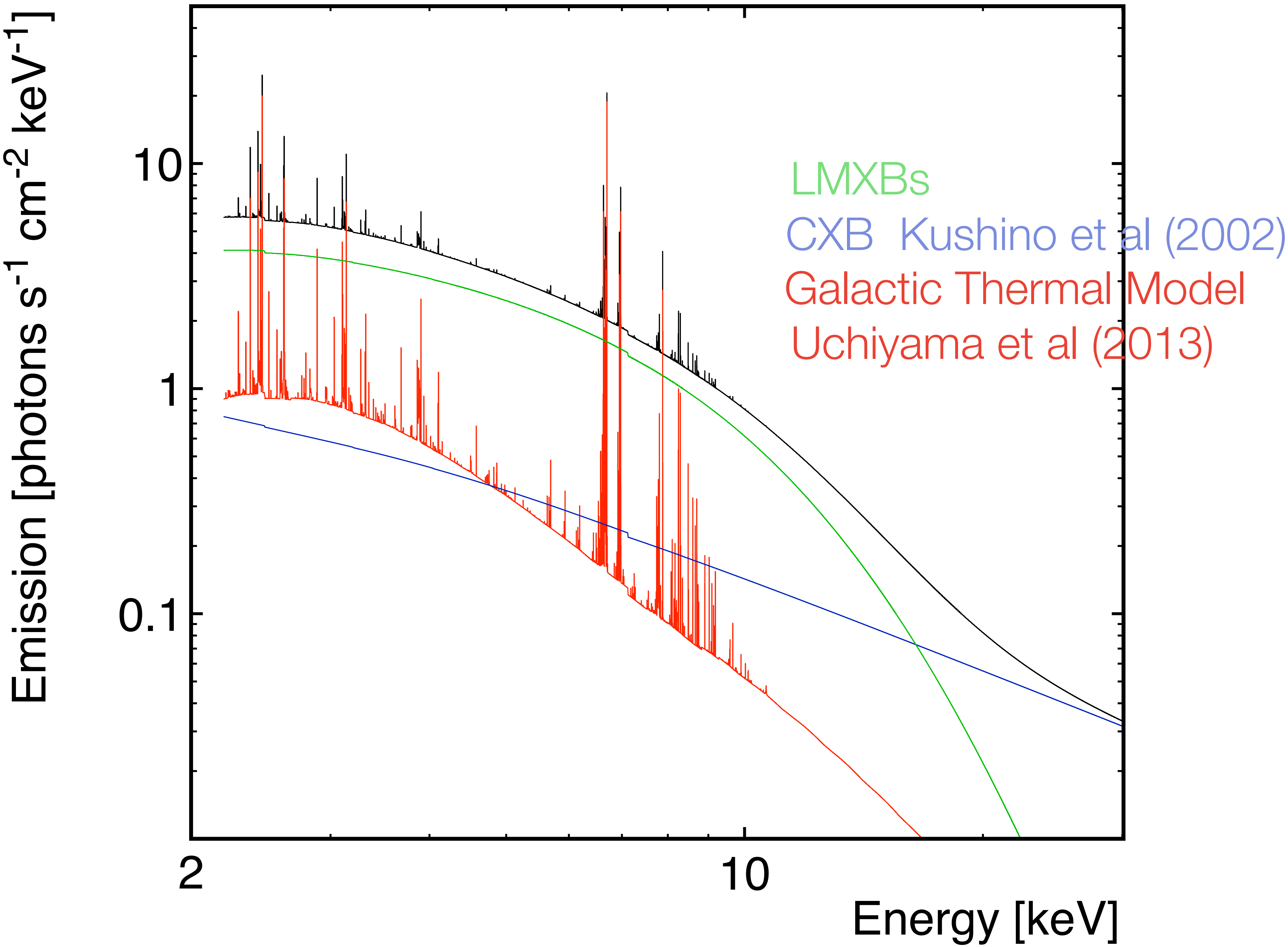

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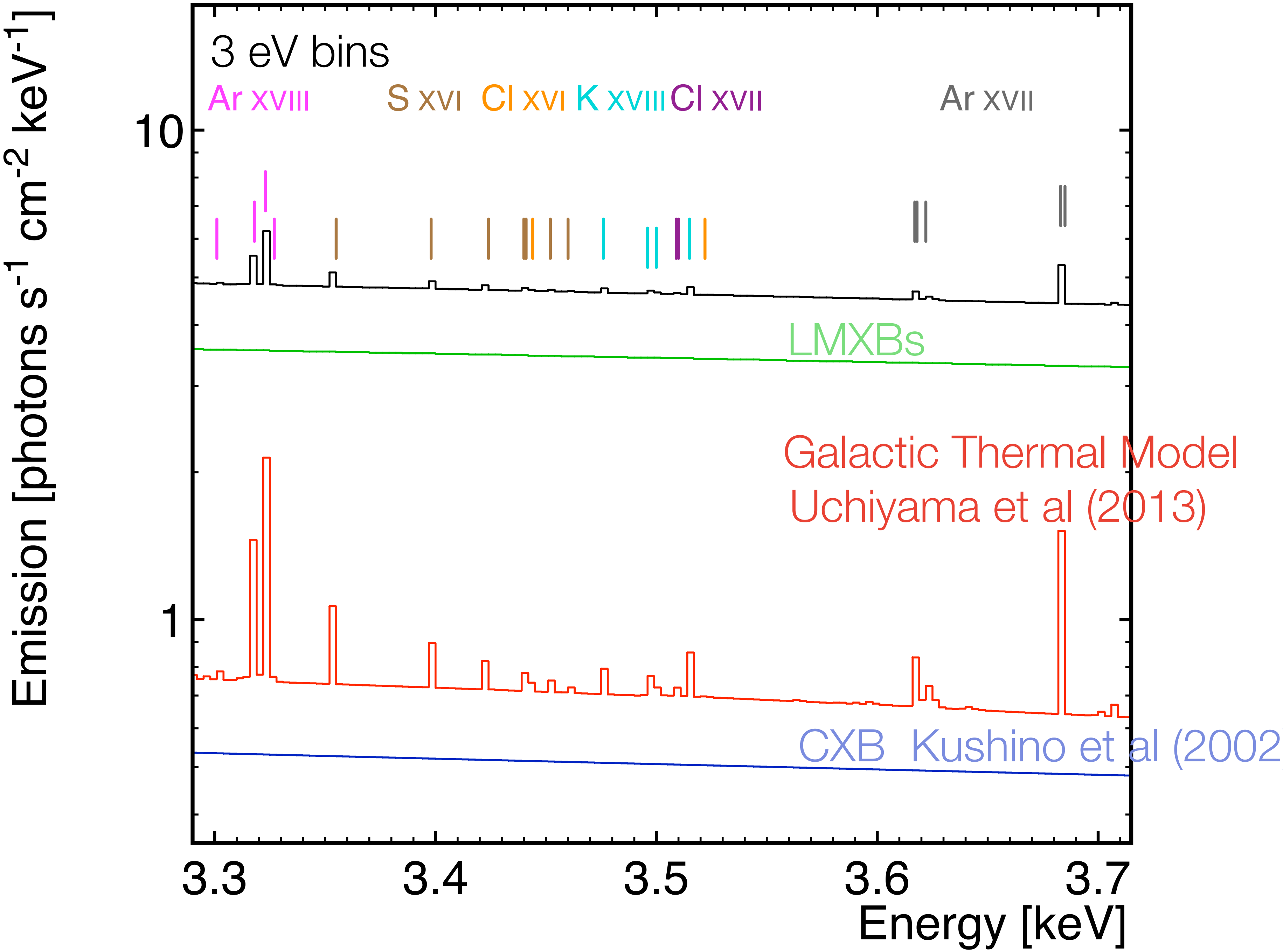
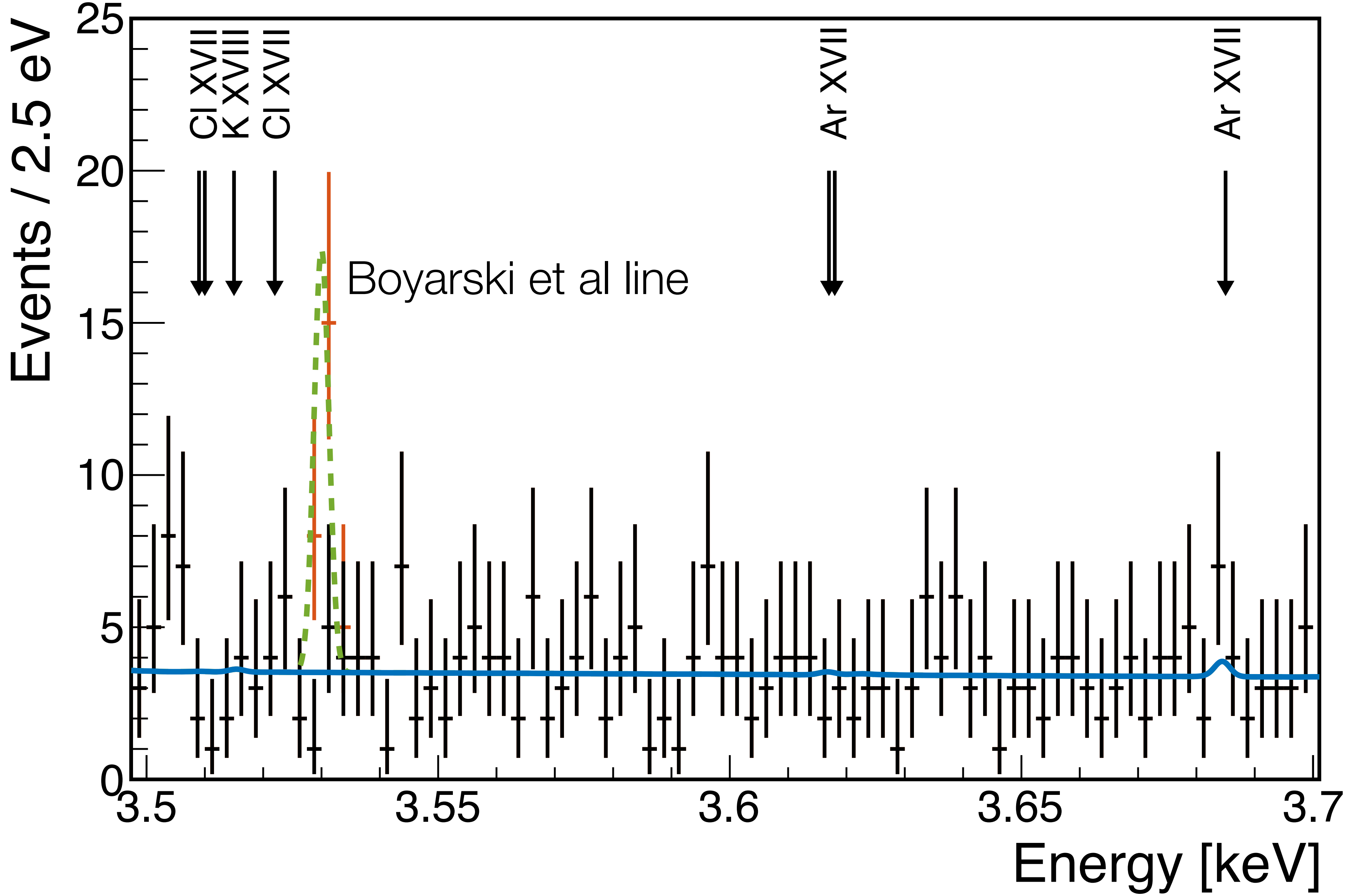
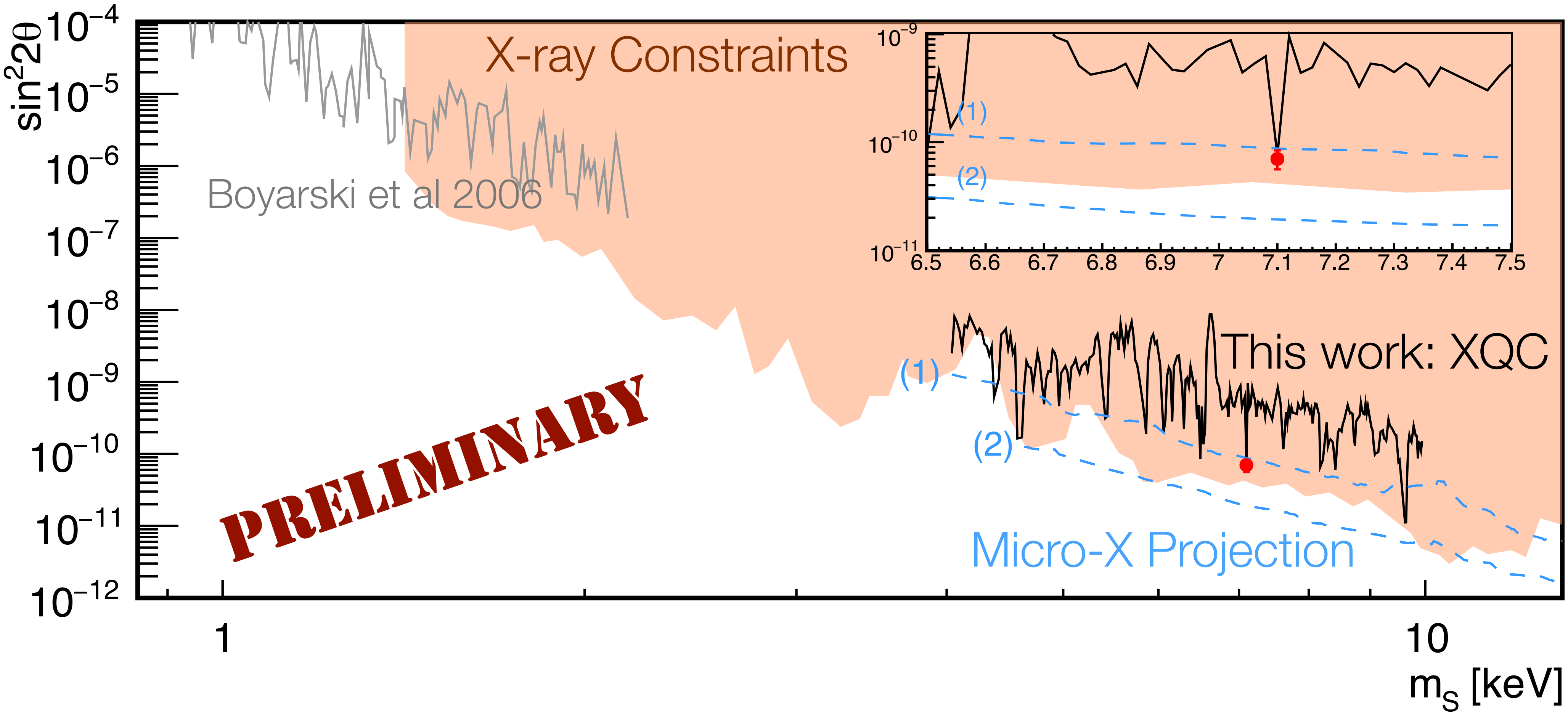


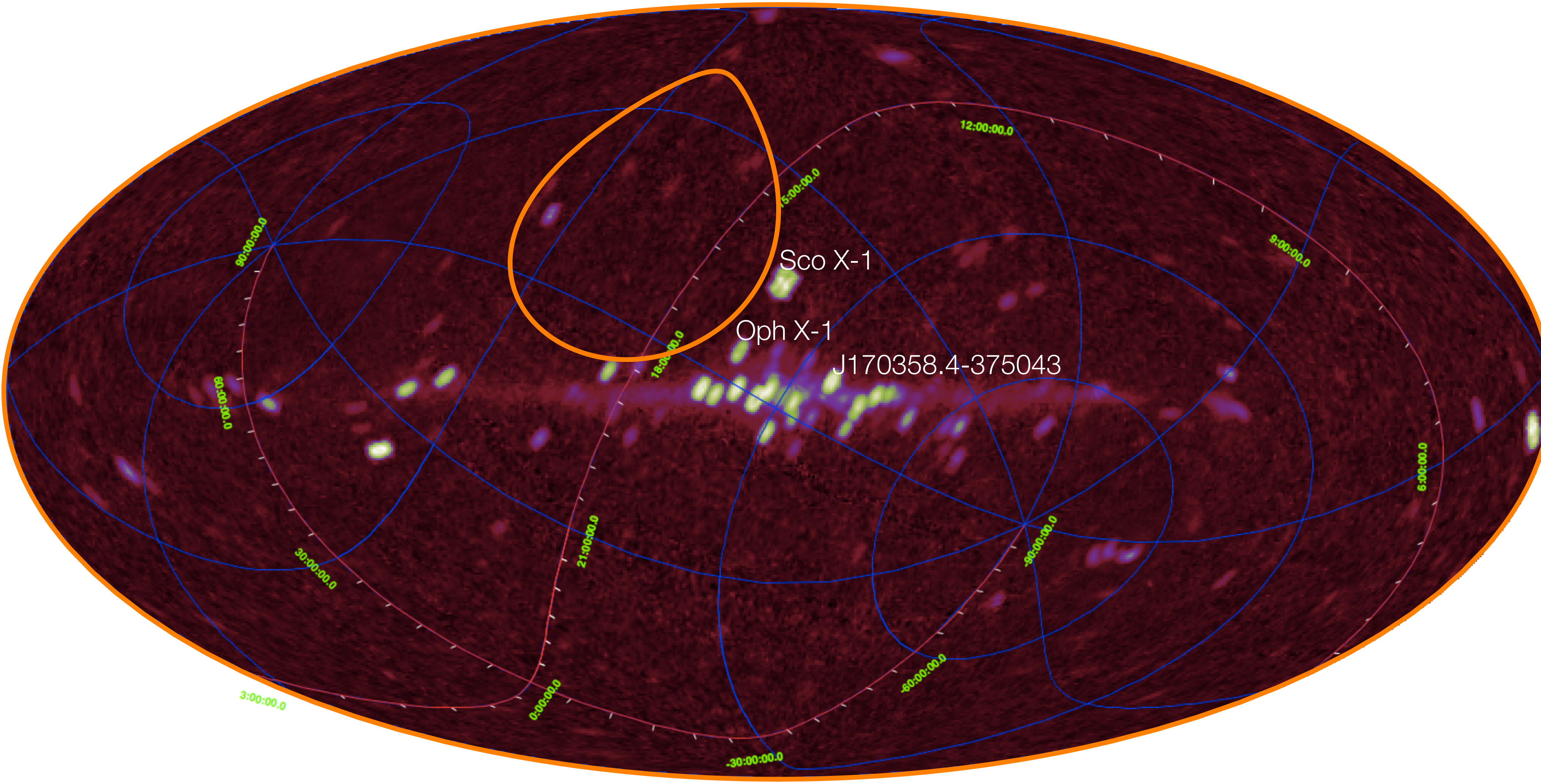
Mock Micro-X GC Observation



Sterile Neutrino Bounds

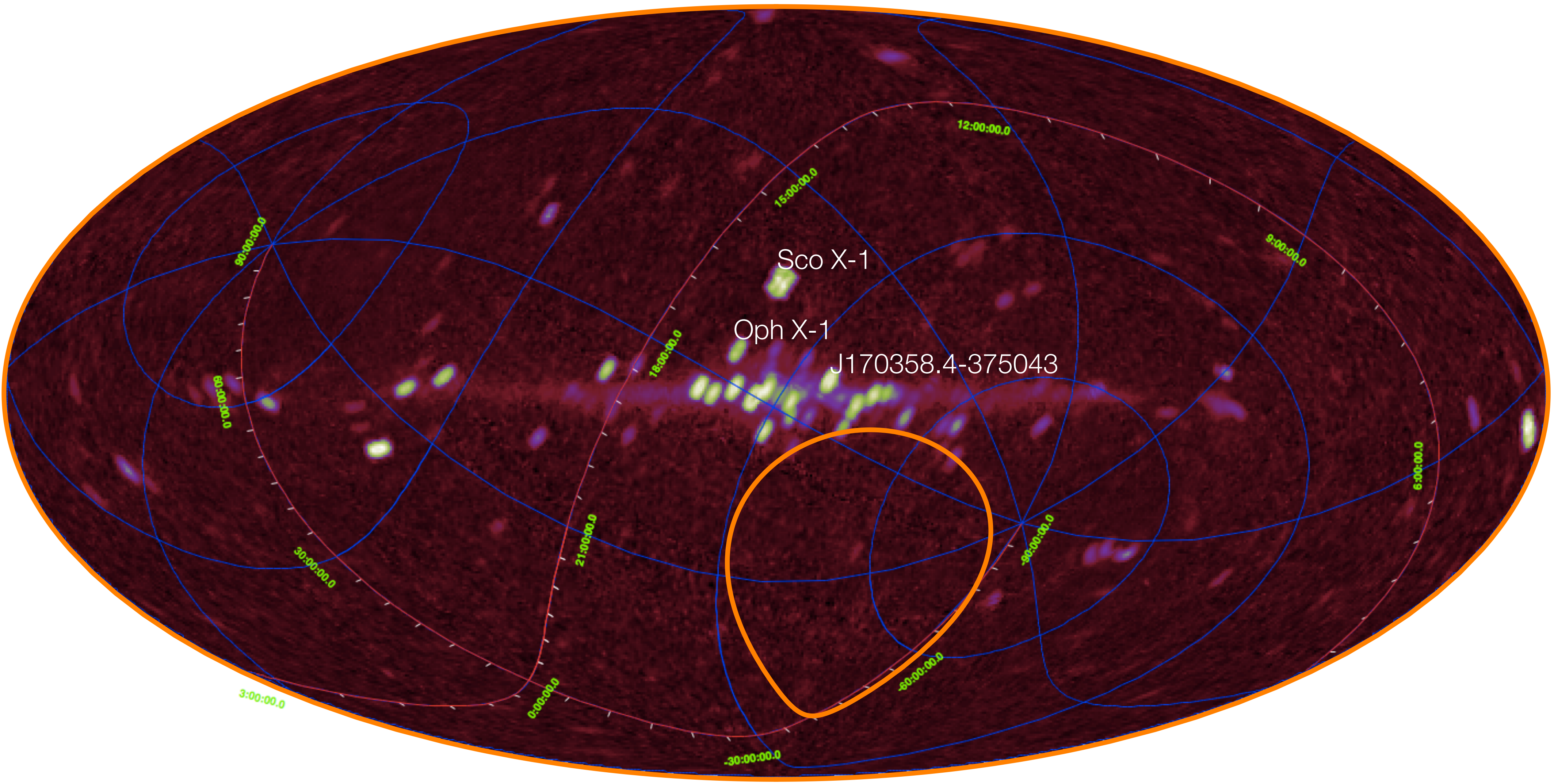


Future FOV for Micro-X: 1 sr, Off-Plane



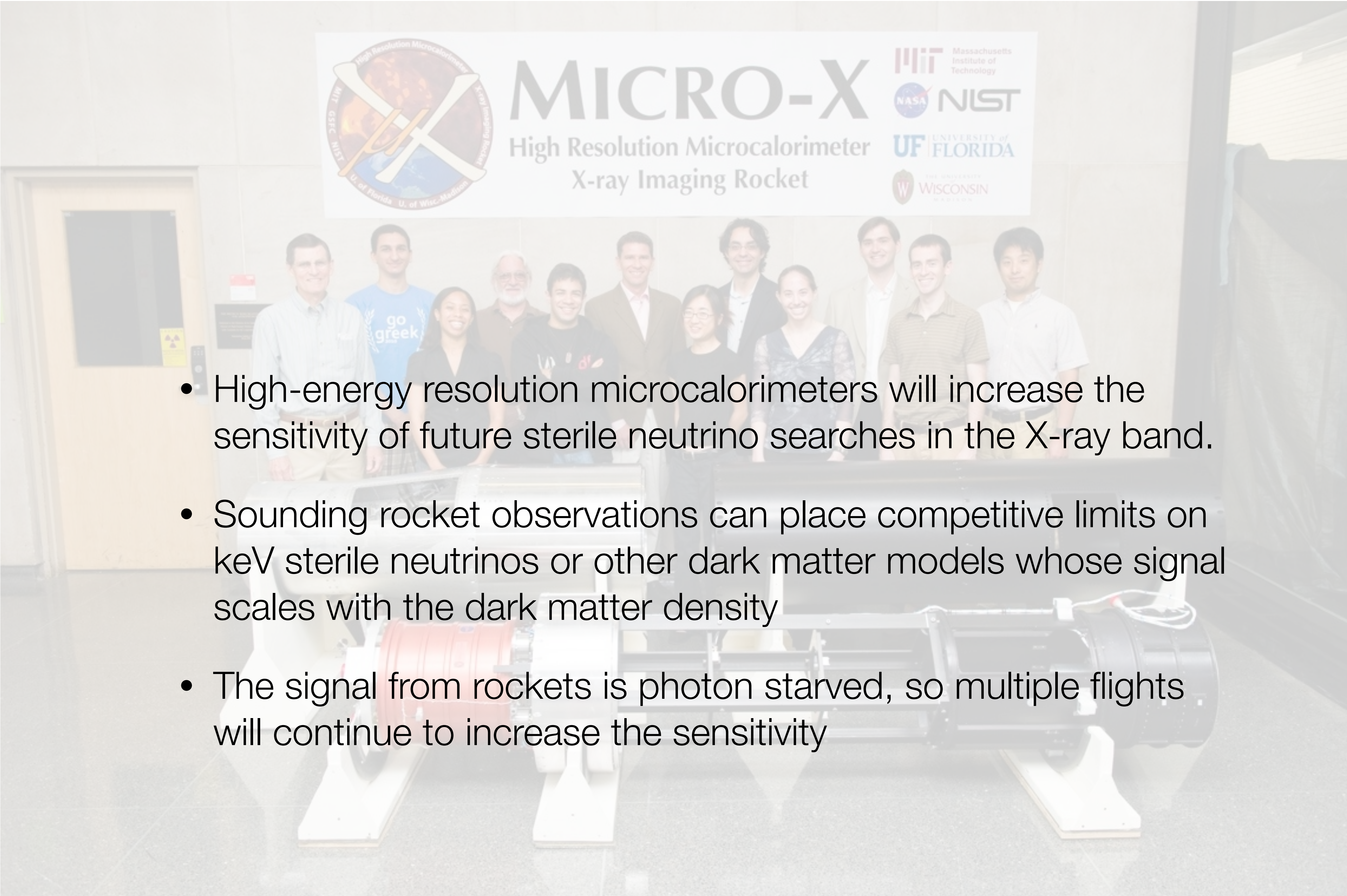
Einstein 2-9 keV All-Sky Map

Future FOV for Micro-X: 1 sr, Off-Plane



Einstein 2-9 keV All-Sky Map

Conclusions



- High-energy resolution microcalorimeters will increase the sensitivity of future sterile neutrino searches in the X-ray band.
- Sounding rocket observations can place competitive limits on keV sterile neutrinos or other dark matter models whose signal scales with the dark matter density
- The signal from rockets is photon starved, so multiple flights will continue to increase the sensitivity